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Straw Bale Construction: The Application in Massachusetts

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Magwood, C., & Walker, C. (2001)

Major Qualifying Project

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Abstract

Through research and testing procedures, the correlation between various plaster components and straw bale was evaluated in terms of vapor permeability, thermal resistivity, and compression strength in order to assess how applicable a plastered-straw bale system can be relative to cold climate regions. In addition, a one-family, two-story straw bale structure was designed and structurally analyzed for Worcester, MA by following the Commonwealth of Massachusetts State Building Code. A cost benefit analysis was also conducted to see how the costs between straw bale construction and standard construction methods in Massachusetts differ. Through the findings of this project, it was determined that straw bale construction is a viable alternative to standard construction methods in Massachusetts.

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Leonard Albano – Associate Professor of Civil and Environmental Engineering at WPI

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Authorship Page

This report was authored by the following individuals, each had specific authorship responsibilities and each collaborated between disciplines across the completion of the project.

Hajar Jafferji ____________________________

Conducted background research and interviews

Prepared all testing samples and procedures

Documented water portions during mixing

Conducted and documented testing data for vapor permeability tests

Analyzed data results from all compression strength, thermal resistivity, and vapor permeability tests

Analyzed costs of a designed straw bale house and conventional residential structure for Worcester, MA

Karina Raczka ____________________________

Conducted background research and interviews

Prepared all testing samples and procedures

Quantified portion ratios for all specimen batches

Manipulated and analyzed data results from all compression strength, thermal resistivity, and vapor permeability tests

Amended appendices and acted as the final editor for all chapters.

Yao Wang ____________________________

Conducted background research and interviews

Prepared all testing samples and procedures

Conducted testing for vapor permeability tests

Analyzed data results from all compression strength, thermal resistivity, and vapor permeability tests

Analyzed costs of a designed straw bale house and conventional residential structure for Worcester, MA

Conducted structural design of a one-family, two-story straw bale house in Worcester, MA

Capstone Design

In order to fulfill the Capstone Design degree requirement, this Major Qualifying Project considered several real-world constraints. This project realistically addressed the economic, environmental, sustainability, constructability and health and safety considerations through the design, testing, and analyzing processes.

Economic

The economic component of the capstone design consisted of a cost analysis of a proposed, one-family, two-story straw bale structure against a traditional wood-framed structure in Worcester, MA. The cost analysis included material, labor, and mark up costs for both structures. One goal of this project was to determine if straw bale is an economic construction material in terms of both initial and maintenance costs.

Environmental

The environmental section of the capstone design addressed the benefits of straw bale construction in terms of being environmentally friendly. Since straw as well as earthen plaster components are renewable and plentiful resources, they thereby do not mandate excessive energy to be outputted for their utilization. In addition, the utilization of straw bale minimizes the need of other construction materials that are more energy intensive to produce and consume in comparison to straw.

Sustainability

The sustainability aspect of the capstone design associated determining the longevity of straw bale structures. The durability and long-term maintenance aspects of plastered-straw bale walls was explored.

Constructability

The constructability component of the project focused on practicing and evaluating the design-to-build cycle of a straw bale house. This was done by evaluating (1) the actual preparation of small-scale plastered-straw bale system specimens, (2) the compression, shear, and lateral results of the plastered-straw bale specimens, and (3) the structural design of a one-family, two-story straw bale home.

Health and Safety

The health and safety aspect of this project determined the liability and safety of straw bale structures based on how applicable structures can be in terms of abiding to Massachusetts State Building Codes. This entailed determining the structural performance a one-family, two-story wrap-around-frame straw bale structure. Other considerations included the type of labor and materials that could be utilized in straw bale construction and how they differ against standard construction methods.

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1. Introduction

Now more than ever, sustainable construction efforts are being made to mitigate the amount of energy that is used behind the procurement and transportation of construction resources and materials. Currently, 45% of all the energy consumed in the world is used in the manufacture and transportation of such building materials (Earth Garden, 2004). In addition, most standing structures are not in the least bit energy efficient. In the United States alone, as much as 70% of the electricity consumed and 40% of carbon dioxide emitted by residential homes is wasted due to the fact that many structures are poorly insulated and need excessive amounts of electricity and fuel to balance their energy inefficacies (Zeller Jr., 2010).

Energy and resource conservation has become a popular priority in today's construction industry. Whether it is to save energy costs or to genuinely act more sustainably, both commercial and non-for-profit interest groups have been growing more concerned on making buildings more "green". Green characteristics include efficient energy usage, water efficacy, decreased carbon dioxide emissions, increasing the utilization of natural light, and improvements in indoor air qualities (U.S. Green Building Council, 2010). Current sustainable design and construction efforts can make energy efficient homes up to 90% less energy intensive than standard structures that are built to the same building code (Zeller Jr., 2010).

One method of building energy efficient structures is through straw bale construction. Building with straw bales has remarkable advantages that building with conventional materials such as wood, steel and concrete lack in terms of cost, abundance, and sustainability. However, the most distinct advantage of straw bale is that it is a highly efficient thermal insulator.

Although straw bale houses have been built in many areas around the world, as well as in the United States, straw bale construction has not been readily utilized in Massachusetts. The goal of this project was to determine the applicability of straw bale as a construction material in Massachusetts by evaluating the properties of various plaster compositions in conjunction with straw bale. Factors, such as structural strength, thermal capacity and vapor permeability, were evaluated. Through house design and cost analysis activities, the applicability of straw bale construction, in terms of cost effectiveness and ability to abide to Massachusetts State Building Code, was also evaluated.

Using literature findings and the laboratory tested data, conclusions were made on the applicability of post-and-beam wrap-around straw bale structures in context to Massachusetts State Building Code. Favorable components for plasters were also determined for each essential function of plaster; strength, vapor permeability and thermal resistivity. Limitations of straw bale construction in real-world applications, as well as those met in this project, were also recognized. Recommendations for future work regarding straw bale construction evaluations were proposed as well.

2. Background: General Components of Straw Bale Construction

Straw is remarkably strong as it has a similar molecular structure to that of wood. When densely baled together, straw accounts for numerous qualities that are very favorable for construction. A common misconception concerning straw is that it should not be used for construction as most people initially imagine straw to be a loose and unsteady stuffing material. As this is true for individual grains of straw, baled straw is actually a very effective construction material because of its high density. To clarify, the distinction between straw and straw bales can be compared to sheets of paper and a heavy bounded book. As sheets of paper are very weak and unstable individually, they work in the contrary when bounded together. Another misconception concerning straw bale is that it is hazardous in terms of combustion. However, because straw bales are densely compacted, they are actually very fire resistant as there is limited oxygen within the bale to permit combustion.

Building with straw bales has several advantages that building with conventional materials such as wood, steel and concrete lack, especially for energy efficient structures. The most distinct advantage is the high thermal resistivity of straw bales that make buildings thermally efficient. R-value is a number that signifies the thermal resistance of an insulator. Researches to date report the R-value of bales ranges from 5.2 to 10.8 per inch, which is significantly higher than that of wood, which is only 1.0 per inch. In addition, straw bales are more thermally efficient than brick (0.2 per inch) and fiberglass batts (3.0 per inch) (Stone, 2003). It is needless to say that because of the volumetric size of the material, in comparison to the other mentioned materials, straw bale structures are that much more thermally efficient. In other words, a 17-by-19-by-40-inch bale with an R-value of 10 per inch, for example, is much more thermally efficient than a two-by-four-inch piece of lumber with an R-value of one per inch.

In addition to being thermally efficient, straw bale construction is also considered sustainable and economical because straw is renewable and abundant. In contrast to many construction materials, straw can be grown in less than six months and does not call for an exorbitant amount of energy to produce. For example, it costs 6.15 million kJ of energy to manufacture one ton of concrete where it only costs 119,250 kJ of energy to produce one ton of straw (Earth Garden, 2004).

2.1. Construction Methods

When building with straw bales, two fundamental types of construction methods can be applied: the load bearing method, and the wrap around method.

The load bearing method entails for straw bale walls to support all the loads that a structure encounters (e.g. roof, floors, snow, etc.). Under this method, walls are generally created by stacking bales of straw together so that there are no gaps or spaces between them, and corners are interlocked so that they join together. Advantages in this method include easier construction than conventional building methods and significant reductions in the need of other building materials (e.g. wood, concrete) (Steen & Bainbridge, 1994).

One major disadvantage concerning the load bearing method is the limited size of the structure. The larger a load bearing straw bale structure is, the more difficult it becomes for the structure to stand and resist the loads that are acting upon it. Another negative aspect includes the fact that straw is more prone to settle under this method and thus may require frequent maintenance (Steen & Bainbridge, 1994).

Straw bale can also be utilized in the wrap-around method. Under this application, straw bales play the role of an insulator instead of the primary load bearing material (Mack & Therrien, 2005). Structural frames within wrap-around straw bale structures do not significantly differ from traditional construction methods; materials can be composed of wood or steel, and frames such as stick, timber and post-and-beam methods can be utilized. As long as a framework is structurally supportive, there are few architectural design limitations to using straw bale as a wrap-around material because it is so malleable. Below are two examples of different architectural scheme used on the same construction method.

Figure 1: Straw Bale House in Deering, NH, Courtesy of Ace McArleton

Figure 2: Straw bale House in Barnet, VT

Figure 3: Timber Post of House in Barnet, VT

2.2. Interior and Exterior Finishes

As straw bales are most vulnerable to rainwater and excessive moisture, the main purpose of finishing a straw bale wall is to protect the bales from water and vapor intrusion. Choosing an appropriate exterior finish is a critical aspect in straw bale construction because different plaster-finish compositions will react differently to various weather conditions.

There are a few factors that are considered when to choosing an exterior and interior finish. One factor is preference. Clay-and-lime-based earthen finishes, for example, are favored over cement stucco plasters due to their ease of application, aesthetic appeal and because they deter the intrusion of moisture (Lacinski & Bergeron, 2000). A second factor includes whether or not a finish should supply any structural support. For example, larger load bearing structures, or buildings in seismically active zones or in heavy snow-load regions, may require wire-reinforced cement stucco for additional structural stability for resisting both compression and shear loads (Lacinski & Bergeron, 2000). A third factor, and the most critical factor in regards to cold climate application of straw bale construction, characterizes the vapor permeability, or the breathability, of the plastered bale walls. It is essential that plasters have the ability of diffusing water vapor through straw bale walls in order to release moisture, which would otherwise cause internal damage to a structure (Steen & Bainbridge, 1994). Although higher vapor permeability may contribute to heat loss through walls, the unique characteristic of straw bales requires the breathability of the plaster.

2.2.1. Cement

Cement is highly regarded as an effective general construction material due to its exceptional structural and impermeable properties, but it proves to be counter effective in terms of straw bale construction for wet and cold weather regions because of its low vapor permeability capacity. Cement stucco plasters for straw bale structures are primarily used in regions that experience infrequent horizontal weather (i.e. rain, wind) as well as long durations of dry heat (Lacinski & Bergeron, 2000). In an ideal state, a cement stucco finish would be very effective in protecting bales in any climate. However, since it is almost impossible for cracking not to occur in cement because of its rigidity, especially when applied to a malleable backing material like straw, moisture and water would inevitably come in contact with the bale walls (Lacinski & Bergeron, 2000). Consequentially, this would result in the bales rotting as the moisture within the wall would have no means of escaping due to the fact that cement is so impermeable (Jones, 2001).

2.2.2. Earthen Plasters

Earthen types differ but generally consist of about 20% clay to 80% sand for both interior and exterior plasters (Jones, 2001). Some examples of components in earthen plasters include clay and or lime as binders, sand as the aggregate material, and chopped straw and or manure as fiber (McArleton & Racusin, 2010). Hydrated lime and clay have been used to bind stone and brick as a building finish for thousands of years (Jones, 2001). When applied appropriately, both hydrated lime and clay are very pragmatic binders for a plaster finish as they are both flexible materials for mixing, durable when dry, and allow for vapor permeability. Manure has also been used within earthen plasters for centuries, primarily as it makes a plaster more workable. Cow manure is preferable for plasters as the digestion tract of cattle incorporates more enzymes which leave a more fiberous end-product than most types of manure (e.g. horse) (McArleton

& Racusin, 2010). Contrary to popular belief, manure does eventually become non-odorous, and is safe to use because the hydrated lime within a mix is able to chemically react to the manure to kill any existing bacteria. Manure is also believed to withstand great tensile stresses, yet not much research has been conducted to deduce this belief (McArleton & Racusin, 2010).

Deciding the composition of an earthen-based batch is not fundamentally based on each individual ingredient, but how all the composed ingredients complement one another to make an effective mix. As any mortar mix needs certain quantities of binder, aggregate, and fiber components to be effective, the quantities of the materials within one of these three components can be managed to fluctuate, as long as the other component materials will be able to compensate for a weak contributor in regards to the overall composition of the mix. For instance, if the availability or quality of one ingredient (e.g. manure) is low, the quantity of other materials (e.g. straw) could be increased to compensate for the loss in that component (e.g. fiber) to the overall mix. More water could also be added to compensate for the loss of adhesion that would have been provided by the manure (McArleton & Racusin, 2010).

Depending on the function of a specific plaster-coat, different grains of sand will affect the coarseness and thickness of a coat. It is important to consider the size of an aggregate's grain while composing a plaster mix as the structural integrity of a plaster is most dependent upon the aggregate. A base coat, for example, should be very coarse while the final coat should be finer. This ensures that the base coat can be easier applied onto the straw and the finish of the wall looks smooth. The thickness of a plaster coat should be three-times the size of the aggregate's largest grain. Lime wash or lime plaster, which is usually just composed of hydrated lime, sand, and sometimes manure, is usually applied as a final finish coat as the lime protects the base coats from weathering (McArleton & Racusin, 2010).

Earthen plasters are favorable to use in straw bale construction as they are vapor permeable, easy to work with, nontoxic, reusable, usually inexpensive and good sound absorbents. The only energy involved in manufacturing an earthen finish is spent in digging, transportation and in some cases, milling (Lacinski &

Bergeron, 2000). Based on the finish consistency, weather conditions during application, method of application, and other conditions of application, plastering durations can last anytime between a few days to months (Earth Garden, 2004).

2.3. Relationship with Other Construction Material Elements

All kinds of code-approved foundations, floors and roofs that are used in traditional construction can also be used for straw bale construction in terms of structural support. In addition, methods for installing plumbing and electrical inputs are also very similar. However, some special considerations need to be made in terms of design and construction elements in order to prevent excessive moisture intrusion and thermal bridging. For example, the tops of foundation walls should be about 16 to 24 inches above the finish grade of the site to prevent the bottoms of bale walls from meeting moisture (Appendix E). Air-fins are used between the frames and bale walls to compensate for thermal bridging. Also, roof overhangs are recommended to be exaggerated in order to minimize the amount of weathering that is met by the exterior walls. In addition to the framework, exterior, non-structurally supportive frames are also often built to support the openings for doors and windows. Because of the great width of bales, some extra insulation may also be used in areas, such as in between rafters or within the foundation (Appendix D: Notes from Conference Call with Ace McArleton (11/30/10). Figure 4 illustrates a section view of a straw bale construction wall.

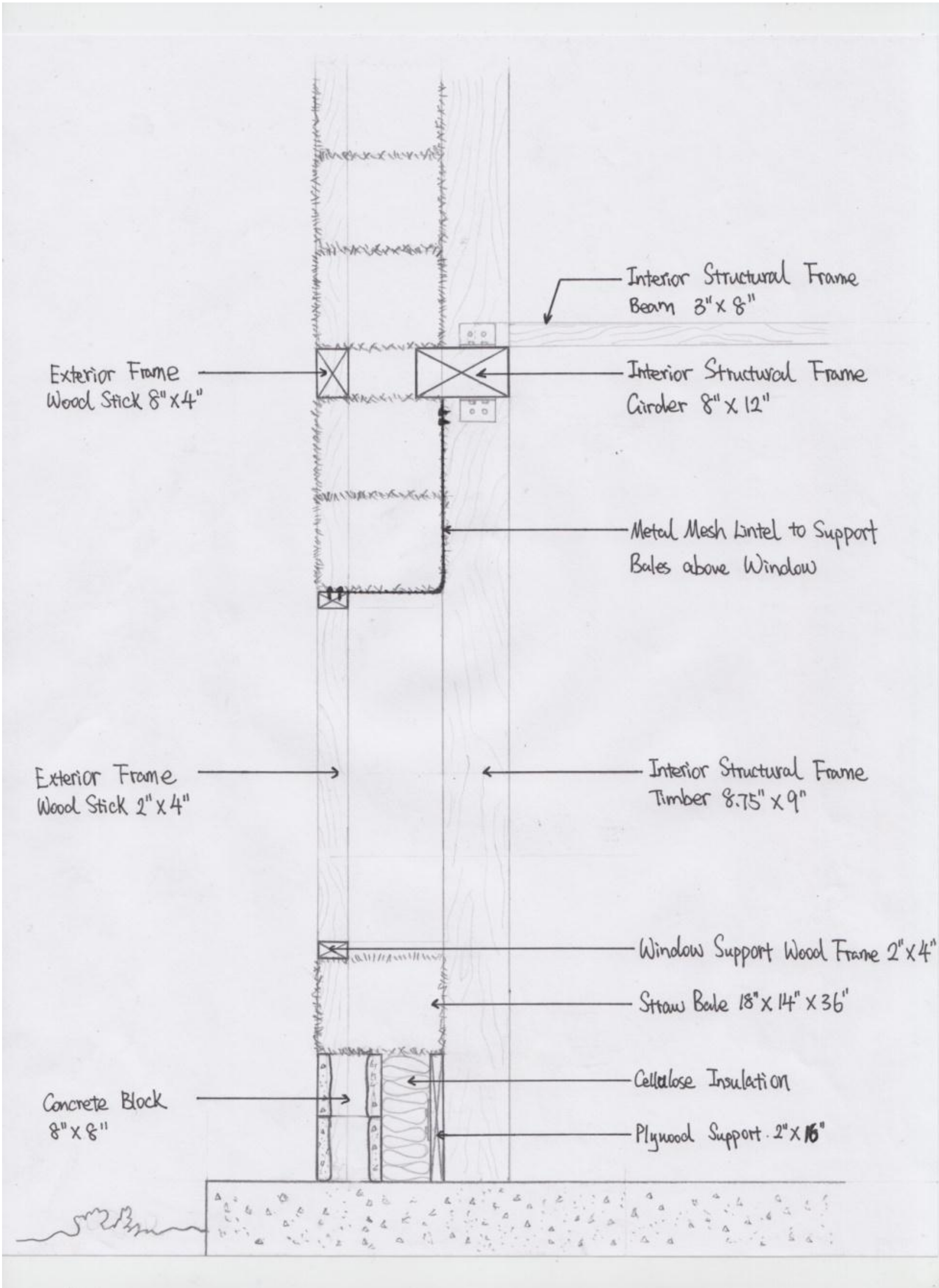

Figure 4: Section of Straw Bale Construction Wall

2.4 Structural Analysis of Straw Bale Construction

There is a great variance when constructing a load bearing straw bale structure compared to one that is a wrap-around. The key difference is that the straw bales of a load bearing building must withstand all loads, whereas a wrap-around building has a frame that carries the majority of loads. As mentioned in Section 2.1. Construction Methods, the straw bales in a wrap-around structure are placed within the frame and act an insulator. With all the aspects to be considered when designing and building with straw bale, the principle factor to regard is the structural behavior of the material, especially for load bearing structures. The fundamental theory behind designing any load bearing structure includes determining how loading conditions (e.g. wind, snow, seismic, dead, live, etc.) disperse throughout a structure from the initial impacted areas (King, Straw Bale Construction, 2005).

In straw bale structures, for both load bearing and wrap-around structures, it is essential to regard the finish-plaster as the initial load-carrying element. However, as a plastered wall will transfer load forces throughout the bales and to the foundations, it is essential to evaluate all aspects of straw bale components, even if they are not structurally supportive (i.e. bales in a wrap-around structure), to see how they can withhold such forces. Moreover, the plaster which is placed on the straw bales of both a load bearing structure and a wrap-around plays two roles: (1) it helps increase the strength of the building and (2) makes sure the bales can "breathe" so that air can transfuse in and out to reduce moisture from accumulating within the bale walls.

Although both types of structures can be used in forms of construction, the method that is more frequently employed is the wrap-around. Since straw bale construction is still not as widespread, building inspectors within Massachusetts are more likely to approve a straw bale structure that has a frame (Albano, 2010). Accordingly, this project prominently focuses on wrap-around style straw bale structures.

There has been research completed on straw bale structures in which researchers evaluated both load bearing and non-load bearing building approaches. Generally, within each study, different parameters and areas of interest were taken into consideration. For example, various studies have looked into compressive tests of straw bale walls. However, each individual study has a unique focus and test. One test performed a compressive test on straw bales with certain moisture contents and another experiment focused on compression strength tests on straw bale walls with various plasters (King, LOAD-BEARING STRAW BALE CONSTRUCTION, 2003). In this project, the relationship between finish-plaster and straw bales was investigated through physical testing to evaluate how they can perform together structurally within a load-carrying system and collaboratively with a wrap-around structure. More specifically, tests such as vapor permeability, shear, lateral, compression and thermal resistivity, were conducted on bale as well as plaster specimens.

2.5 General Design Principles for Residential Structures

As straw bale structures may differ from standard home constructions in terms of structural aspects, the fundamental architectural aspects of a straw bale home can either mirror traditional homes or be widely exaggerated. Designing a residential structure for comfortable living is often incumbent on the demands of a home's inhabitants. Although many designs and trends will differ in order to comply with a client's degree of lifestyle, several basic principles are foreseen in many modern households. Some major features of all modern homes include a large, multi-purpose common area and an office area that serves as a workspace. Commonly, a workspace is desired to be set aside from the rest of the house as a way to separate work and personal time from within the home (Adler, 2006).

As much as homes are catered to social considerations, a chief aspect that also should be incorporated into the blueprint of a house is an environmentally friendly and energy efficient design. In doing so, many architects have adopted the principles of passive solar design. One aspect that fulfills eco-friendly design is room and window placement. Windows and rooms that are most likely to be utilized should be placed on the south side of a home in order to optimize the amount of sunlight that hits the house. This minimizes the amount of artificial lighting and heating that is needed for the home. Also, another way to infuse a residence with a passive solar design is by laying out the bedrooms to be on the east side of a home so that the residents can wake up with the sun as it rises in the morning (Mazzaria, 1997). Since building an environmentally friendly home is significant, these architectural principles were taken into consideration when designing a one-family, two-story straw bale house in Worcester, MA.

2.6 Commonwealth of Massachusetts State Building Code (780 CMR)

Just like any other building, it is crucial that straw bale structures abide to a building code. It is necessary for anyone constructing with straw bale to investigate state building code and analyze all the aspects that encounter the erection of a straw bale building in careful context to the code. Abiding to codes is not only essential to obtain occupancy, but exceeding the minimum requirement of codes shall substantiate assurance for building inspectors, especially if their general understanding of straw bale construction is undeveloped.

The current applicable state building code for Massachusetts is the Seventh Edition of Commonwealth of Massachusetts State Building Code, *780 CMR*, that is based on the ICC International Building Code 2003 with significant Massachusetts modifications (Commonwealth of Massachusetts, 2008). *780 CMR* consists of two volumes: one addresses all building uses except one-and-two-family dwellings, and the other addresses only one-and-two-family dwellings. Since most straw bale construction practices regard residential homes (Steen & Bainbridge, 1994), it was decided to primarily investigate the second volume of *780 CMR*; one- and two-family dwellings.

The second volume of *780 CMR* lists the minimal requirements of several residential construction aspects. This includes design loads; layout planning; approved types of materials; approved types of construction for foundations, floors, walls and roofs; and energy efficiency. The use of alternative materials, appliances, equipment or methods of design or construction shall be approved when the said alternative is satisfactory and complies with the intent of the provisions of *780 CMR* approved materials and methods of construction in quality, strength, effectiveness, fire resistance, durability, and safety (Commonwealth of Massachusetts, 2008).

In the case of straw bale construction, the primary concerns in abiding to *780 CMR* lies in the structural design and construction, specifically for interior and exterior wall systems. Therefore, one scope of this project was to determine the structural analysis of straw bale walls and determine how they can abide the contexts of *780 CMR*. Additionally, since thermal resistance is the most distinct merit of straw bale construction, the energy efficiency aspect of the material in the context of the *Energy* section 61.00 of *780 CMR* was also evaluated.

3. Methodology

Amongst all the types of exterior finishes, three popular utilizations of plasters in straw bale construction are based with lime, clay, and cement binders (Earth Garden, 2004).The most commonly used plaster in cold climate regions is earthen based because of its vapor permeability capacities. Even though earthen-based finishes have not been widely tested in certain high-load environments, it is possible that these materials are capable of resisting significant structural loads (Lacinski & Bergeron, 2000).

In this project, various combinations of binder, aggregate and fiber compositions of earthen-based plasters were explored in terms of vapor permeability, thermal resistivity, and compression strength. As concrete is such a widely used material, cement-based plaster specimens were also tested and analyzed in comparison to the earthen-based specimens. The correlation between various plaster components and straw bale was evaluated in terms of vapor permeability, thermal resistivity, and compression strength in order to assess how applicable these systems can be relative to cold climate regions.

In addition, the literature, laboratory, and consulting findings were used to design a two-story straw bale wrap-around residential structure for Worcester, Massachusetts in context to *Commonwealth of Massachusetts State Building Code (780 CMR)*. Using these findings and by abiding to the capstone design aspects, it was determined how applicable straw bale can be as a construction material in Massachusetts.

3.1. Determination of Specimens and Methods of Testing

The purpose of this project was to evaluate specific components of straw bale construction. It was deemed essential to incorporate and analyze as many realistic factors within a large-scale application of a straw bale-wall system. Initially, some specimen design configurations entitled applying plasters onto full-sized bales, creating multiple specimens of various configurations, and testing them under several conditions[1]. However, because of the limited space in the WPI laboratory, it was decided to scale down the project and test most of the plasters and bales as separate components. In order to determine how the plaster and bale

[1] For an extensive explanation of the original methodology for this project, refer to Appendix J: Project Proposal

components could work collaboratively within a system, it was decided that extrapolating the test findings of the individual components and using inductive reasoning would be sufficient. In addition, studying the behaviors of singular components would allow to distinguish the most critical factors within a system.

A total of seven full-sized bales were tested in this project. There were two forms of plastering configurations that were applied onto these bales. One configuration involved encasing a bale in plaster on five sides. Two bales underwent this configuration: one with the cement-and-lime-based plaster and the other with the earthen-based control plaster. This configuration was designated to test the thermal resistivity of each plastered bale.

A bale was only plastered on two opposite sides for the second configuration. Four bales underwent this configuration with the earthen-based control plaster. This configuration was designated to test the structural integrity of the plastered bale through compression, lateral, and shear load applications. A more detailed explanation of these testing methods can be found in Section 3.5: Preparation of Testing Samples.

All the plaster specimens were cast in cylindrical molds of either three-inch diameter and six-inch height, or six-inch diameter and four-inch height. Two molds were made per each designated configuration. The list of configurations for the plaster specimens is discussed in Section 3.3: Summary of Specimen Testing Configurations.

3.2. Determination of Dry Ingredient Compositions for Testing Samples in Plasters

3.2.1. Design of Lime-and-Cement-Based Plaster Mix

As mentioned in Section 2.2.1: Cement, cement stucco is favorable in terms of durability, and low maintenance cost. Such qualities would be suitable for weather and loading conditions in Massachusetts. However, as cement stucco does not allow for high rates of vapor permeability, lime is often added to cement stucco to neutralize this imbalance. In order to mimic realistic applications of cement in straw bale construction, a lime-and-cement-based cement plaster mix was chosen to be tested. According to one manufacturer of Portland Cement, Quikrete, the recommended composition for a lime-and-cement mix is

2:1:9 of portland cement to hydrated lime to plaster (play) sand (Quikrete).This composition is based on compliance to ASTM standards.

It was deemed favorable to compose a cement specimen of an optimum caliber in terms of structural integrity, so a reinforcing fiber was incorporated within the cement mix. *STRUX® 90/40 Synthetic Macro Fiber Reinforcement* was used as the polyethylene fiber because of its availability in the WPI workshop. Based on the polyethylene provider's specifications, which is to use 3.0 to 11.8 lbs. of fiber per cubic yard of concrete (W. R. Grace & Co.-Conn., 2006), the design initially incorporated to use 11 lbs. to approach a best case scenario of structural integrity. However, while adding the fiber to the cement mix, it was determined that adding only 5.5 lbs. per cubic yard of plaster cement seemed sufficient because the mix would have been too grainy if more fibers were added.

3.2.2. Earthen Plasters

Utilizing adequate materials for testing was essential for quantifying realistic applications of earthen plasters in cold climate regions. However, as there currently are no standards on plaster finishing governing its composition, mixing, or application for straw bale construction, most of the literary findings in the research exemplified very diverse strategies for mixing compositions and procedures. A natural building professional, Ace McArleton, who was based out of Montpelier, Vermont, and specialized in straw bale construction, was consulted for this project.

McArleton advised that the most desirable plaster for cold climate applications concerning straw bale construction is an earthen-based plaster that consists of variable concentrations of clay, sand, hydrated S-type lime, manure, straw and water. These compositions are most often determined on site and are based on the local availability of materials and the quality of those materials. As mentioned in Section 2.2.2.: Earthen Plasters, compositions of earthen components can vary widely and can still produce an effective mix.

In order to establish a credible base of earthen materials, a spectrum of different compositions of earthen-based plasters was determined to be tested. It was decided to test the following earthen-based batches: an empirically chosen earthen-based composition as suggested by McArleton, a lime plaster, three plasters with different lime-to-clay ratios, and three plasters with different manure-to-mix ratios.

3.2.3. Design of Earthen-Based Control Plaster Mix

According to McArleton, the most ideal earthen plaster should have a ratio of approximately 1:2 to 3: 0.5 to 1 of a binder to aggregate to fiber ratio. To be more precise, it should be a 3: 0.5: 7 to 9: 0.5: 1 to 3 ratio of clay to hydrated lime to sand to manure to straw. McArleton's favored plaster recipe was chosen to be used as the control sample. This sample would then be benchmarked against different compositions of the same components.

While designing the mix recipe, it was recognized that quantities of the overall compositions would be subject to change as the qualities of the individual components would not be known until the time of mixing. It was decided to rely on McArleton's expertise hand and empirical experience to mix the earthen batches and change the portions of the compositions as she deemed necessary for workability and cohesiveness. Until then, the following portions of the design mix were approximated, as shown in Table 1.

Table 1: Design Mix of Earthen-Based Control Plaster

Binder 1	Binder 2	Aggregate	Fiber 1	Fiber 2	Water
Clay	Lime	Sand	Manure	Straw	Water
3	0.5	7-9	0.5	1 -3	TBD
1		2-2.57	.43-1		TBD

3.2.4. Design of Different Binder and Fiber Ratio Mixes

It was deemed essential to test a spectrum of composition ratios of binders, aggregates and fibers to determine how effective certain components were in terms of vapor permeability, thermal resistivity and structural integrity. The focus of testing these specimens was to observe the independent properties of the components in relation to either the mix or between two singular components. This was to evaluate the influence of different constituents in the mix and determine an optimum mix ratio that could be utilized in a real-world application of straw bale construction in cold weather applications.

Three configurations of different lime-to-clay batches were designed. The aggregate and fiber component ratios were to be consistent with the control mix recipe, while the compositions of the clay and lime varied. See Table 2.

Table 2: Design of Lime-to-Clay Batch Ratios

	Binder 1	Binder 2	Aggregate	Fiber 1	Fiber 2	Water
	Clay	Lime	Sand	Manure	Straw	Water
Earthen w/ 10% lime-to-clay	0.9	0.1	2-2.57	0.5	1-3	TBD
Earthen w/ 30% lime-to-clay	0.7	0.3	2-2.57	0.5	1-3	TBD
Earthen w/ 50% lime-to-clay	0.5	0.5	2-2.57	0.5	1-3	TBD

Three configurations of different manure-to-mix batches were designed. The aggregate, binder and straw component ratios were to be consistent with the control mix recipe, while the compositions of the manure portions varied. See Table 3.

Table 3: Design of Manure-to Mix-Batch Ratios

	Binder 1	Binder 2	Aggregate	Fiber 1	Fiber 2	Water
	Clay	Lime	Sand	Manure	Straw	Water
Earthen w/ 10% manure-to-mix	0.86	0.14	2-2.57	0.45	1-3	TBD
Earthen w/ 25% manure-to-mix	0.86	0.14	2-2.57	1.125	1-3	TBD
Earthen w/ 40% manure-to-mix	0.86	0.14	2-2.47	1.8	1-3	TBD

As lime mixes are used as the final coats on straw bale houses, it was decided to test the thermal resistivity and compression strength of lime plaster to extrapolate how a lime coat would function in accordance with a base coat. The ratio of lime to sand was designed to be 1:3.

As batch consistencies are dependent on certain qualities of the mix ingredients, the water content of all of these batches was to be determined during the time of mixing when all the materials would be acquired and the qualities of the ingredients would be known.

3.3. Summary of Specimen Testing Configurations

Table 4 summarizes the final configurations of the specimens. Aside from the bales, two specimens were created for each configuration in order to ensure quality assurance.

Table 4: Configurations of Testing Specimens

Test → / Sample ↓		Vapor Permeability	Thermal Resistivity	Compression	Lateral	Shear
Bales	Earthen-Plastered Bale (EB)		EB1	EB2,EB3	EB4	EB5
	Cement-Plastered Bale (CB)		CB1			
	Unplastered Bale (UB)			UB1		
Cylinders	Lime-and-Cement Plaster (C)	C1,C2	C3,C4	C5,C6		
	Earthen-Based Control (E)	E1,E2	E3,E4	E5,E6 (1st Batch) E7, E8 (2nd Batch)		
	Lime Plaster (L)		L1,L2	L3,L4		
	10% Lime-to-Clay	1A,1B				
	30% Lime-to-Clay	2A,2B				
	50% Lime-to-Clay	3A,3B				
	10% Manure-to-Mix	4A,4B		4C,4D		
	25% Manure-to-Mix	5A,5B		5C,5D		
	40% Manure-to-Mix	6A,6B		6C,6D		
TOTAL		16	6	14	1	1

3.4. Determining Quantities of Dry Ingredients

The cylinders needed for the vapor permeability tests were planned to be four inches in height to equal 113.1 cubic inches of mix per each specimen. Based on the design configurations, as seen in Table 4, 16 of these cylinders were needed in total. The cylinders needed for both the thermal resistivity and compression tests were planned to be three inches in diameter and six inches by height to equal 42.41 cubic inches of mix per each specimen. Based on the design configurations, twenty of these cylinders were needed in total; six for the thermal resistivity tests and fourteen for the compression tests. The volume of plaster needed for bales was determined by multiplying the surface area of the bale that needed to be plastered with the assumed plaster thickness; two coats totaling 1.5 inches. Table 5 summarizes the final presumed volumetric quantities of all the batches made for this project. The calculations for these quantities per batch can be viewed in Appendix B: Determining Dry Ingredient Quantities.

Table 5: Total Quantities Presumed for Specimen Batches

Total Quantities per Batch	Total to be made with ~10% waste (in^3)	Total to be made with ~10% waste (ft^3)
Fiber reinforced lime-and-cement-based plaster	4973	2.88
Earthen-based plaster (control)	13844	8.01
Lime plaster	187	0.11
Earthen w/ 10% lime-to-clay	249	0.14
Earthen w/ 30% lime-to-clay	249	0.14
Earthen w/ 50% lime-to-clay	249	0.14
Earthen w/ 10% manure-to mix	342	0.20
Earthen w/ 25% manure-to mix	342	0.20
Earthen w/ 40% manure-to mix	342	0.20

It was determined that the simplest way to portion each ingredient was to measure the amount of mass needed, especially because some of the materials would not have an ideal composition to be measured via volume (e.g. straw, polyethylene fibers). As the portions of the mix recipe are dependent upon volume, accurate measurements of each ingredient needed to be determined in terms of mass. By finding the density of each ingredient, the mass amounts could be found for each portion. The densities were distinguished by filling a five gallon bucket with each material and weighing them on a balanced scale. Table 6 shows an example of the final quantities in terms of volume and mass for the dry ingredients of the first earthen-based control plaster batch.

Table 6: Example of Determined Dry Quantities: Earthen-Based Control Batch No. 1

Earthen-Based Control Plaster - 1st Batch	Clay	Lime	Sand	Manure	Straw	Water		Total (Dry)
Part	3.00	0.50	8.00	0.50	1.00	TBD		13.00
Part of Total	0.23	0.04	0.62	0.04	0.08			1.00
Volume per part for 5 ft3	1.15	0.19	3.08	0.19	0.38	TBD		5.00
Density of part (kg/ft3)	22.00	12.16	46.82	29.68	1.68			
Mass per part (kg)	23.57	2.17	133.77	5.30	0.60	TBD		165.41

Detailed tables of volumetric to mass conversions for all of the plaster mix compositions can be viewed in Appendix B: Determining Dry Ingredient Quantities.

3.5. Preparation of Testing Samples

The following section will discuss how all the materials of this project were acquired, how batches were mixed, and finally, how the specimens were molded and cured.

3.5.1. Acquiring Materials

The straw bales were obtained from Harris Farm in Wethersfield, CT. The bales were tightly bound with two strings, and the typical dimensions were 18 inches tall, 24 inches wide, and 36 inches long. The average density of the specimens was 5.80 lb. per cubic ft. The straw itself was a winter rye seed grain and was cut in June of 2010. A moisture meter was used to record the average moisture content of the bales to be 9.52 percent.

Acquiring appropriate clay and manure for earthen plasters can be difficult as such earthen materials can vary considerably in terms of properties and qualities. As McArleton possessed the empirical experience of judging qualitative properties of such components, specifically in regards to straw bale construction, McArleton provided the clay and manure for the project. A ball clay manufactured by Kentucky-Tennessee Clay Company (Kentucky-Tennessee Clay Company)was used, and cattle manure was acquired from a farm in Vermont the morning of mixing.

It was initially anticipated to use plaster sand for the earthen mixes, yet McArleton specified that plaster sand was too fine and the grains were too uniform for earthen plasters. McArleton insisted that sand, which was already available in the WPI lab, should be sifted with 4.75 mm. sieves. A picture of the utilized sand, along with the manure and clay can be viewed in Figure 5. All the other materials that are mentioned in this report were provided by WPI.

Figure 5: Sand, Manure, and Clay Used in Earthen Mixes

3.5.2. Mixing Batches and Determining Final Water Ratios

The lime-and-cement-based plasters were made in the four-and-a-half cubic yard cement mixer that was available in the WPI laboratory. The dry components were predetermined, as summarized in Section 3.2.1. Design of Lime-and-Cement-Based Plaster Mix. While mixing, Don Pellegrino, WPI's lab technician, added measured portions of water to the batch and anticipated a specific consistency for the mix. The final approximate portions for the 5.5 lbs. per cubic yard of mix are summarized in Table 7.

Table 7: Composition of Fiber-Reinforced Lime-and-Cement-Based Mix, Including Water

Binder 1	Binder 2	Aggregate	Fiber	Water
Portland Cement	Hydrated Lime	Plaster (Play) Sand	Polyethylene	
2	1	9	5.5 lbs/cy	1.8

McArleton oversaw the mixing for the earthen-based plasters. For the specimens that only required a minimal amount of material (i.e. all specimens other than the control batch), a small kitchen mixer was used. The mixer used for this batch, along with all the mixers used to make all the batches for the project's specimens, can be viewed in Figure 6.

Figure 6: Pictures of Mixers Used

The earthen-based control plaster, of which about five cubic feet was needed for the first batch, was all mixed by a rented electric-mortar mixer. However, because the mixer's total mixing capacity was limited to 60 lbs., seven separate, identical batches were needed to be made in order to create the total needed amount of five-cubic feet of mix. The initial five cubic feet of mix was used for the cylindrical specimens as well as the first coatings of the four dual-sided plastered bales and the one five-sided plastered bale.

As eight cubic feet of control mix was needed in total for the project, an additional three cubic feet of mix was made another day using the same component portions. For the second batch, a bigger, gas-fueled mortar mixer was rented. As this mixer was capable of mixing greater volumes than the previous mixer that was rented, it allowed to uniformly mix the ingredients in one batch (refer to the last picture in Figure 6).

It was anticipated that the mix recipes that were designed before mixing were tentative. McArleton chose to add and subtract some portions of certain mixes based on her empirical experience of what an earthen-based mix consistency should be in terms of workability and adhesiveness to straw bale. Water was added in measured portions for each mix. The calculations for determining the water ratios for each mix can be viewed in Appendix C: Determining Water Ratios. The final portions of all earthen-based batches are summarized in Table 8.

Table 8: Summary of Portion Ratios of all Earthen-Based Batches, Including Water

Part →	Clay	Lime	Sand	Manure	Straw	Water	Total
Batch ↓							
Earthen plaster (control)	3.00	0.50	8.00	0.50	1.00	3.04	16.04
Lime Plaster		1.00	3.00			1.82	5.82
Earthen w/ 10% lime-to-clay	0.90	0.10	2.50	0.50	1.00	1.82	6.79
Earthen w/ 30% lime-to-clay	0.70	0.30	2.50	0.50	1.00	1.82	6.79
Earthen w/ 50% lime-to-clay	0.50	0.50	2.50	0.50	1.00	1.68	6.68
Earthen w/ 10% manure-to-mix	0.86	0.14	2.50	0.45	1.00	2.72	7.67
Earthen w/ 25% manure-to-mix	0.86	0.14	2.50	1.13	1.00	1.54	7.17
Earthen w/ 40% manure-to-mix	0.86	0.14	2.50	1.80	1.00	1.39	7.69

3.5.3. Molding, Plastering, and Curing Specimens

Two, full-sized bales were plastered with the cement and earthen-based control mixes. For the cement-plastered bale, a 20-gauge wire mesh was encased around the specimen prior to plastering in order to provide a more adhesive base for the plaster (refer to Section 2.2.1. Cement). Due to the formation of the wire mesh once it was encased around the bale, and due to the fact that the bale was not geometrically bound, there were spaces in between the bale and the surface of the wire mesh. This made it difficult to apply the base coat evenly without leaving too many air pockets. However, it was deemed that the unevenness of the base plaster would not be too much of an issue because this bale was only designated for a thermal resistivity test and not compression strength. The first coat was applied and left to be covered with a plastic bag for 48 hours, as advised by the IBC standards (Portland Cement Association).The second coat was applied, covered with a bag for approximately five days, then left to cure in room temperature for the remaining curing period of 28 days. Figure 7 displays the different stages of preparing the specimen.

Figure 7: Pictures of CB Before and After First Plaster Coat Application

The methods for plastering the earthen-plastered bales differed between coats. For the first coat, or the scratch coat, the main objective for plastering was simply to apply the plaster onto the bales. McArleton gave suggestions as to how to coat the plaster using both hands and a trowel to obtain the best adhesion. McArleton also advised to check for air pockets by pressing against the plaster to see if it bounces back, assuring that there were no air pockets within a bale's surface and the plaster coat would help clear voids that would otherwise affect testing results. After the first coats of plaster were applied, scratches were applied to each bale specimen to ease the adhesion process of applying the second batch of plaster. See Figure 8. The second coatings were less laborious as the adhesion between the final coats and scratch coats was more apparent than it was between the scratch coat onto the bare straw. As time was a limiting factor in this project, it was decided not to apply more than two coats of plaster onto the bales in order to assure that the specimens would cure entirely before testing.

Figure 8: Dual-Sided, Earthen-Plastered Specimens After One Coat

In order to assist the plastered bales to cure and to prevent them from cracking, the earthen-plastered specimens were initially covered with plastic bags. However, the plastic soon proved to be ineffective as the plaster started to grow mold on the surface. A possible explanation for this mold growth would be that moisture accumulated at the surface of the plaster from within and was not able to release into air because plastic bags were not highly vapor permeable. As an alternative solution, old bed sheets were acquired to cover the plastered bales and misted them. This ensured that the specimens could simultaneously 'breathe' and be moist. Fans were also provided to enhance the curing process. The duration between the first and second applications was approximately five days while the duration between the second coat and specimen testing was well over 28 days.

For the cylindrical specimens, 16, six-inch wide by eight-inch tall cylinders and 20, three-inch wide by six-inch tall cylinders were prepared to mold the specimen batches. The eight-inch tall cylinders were only filled half way to create the six-inch wide by four-inch tall cylindrical specimens. All of the cylindrical molds were AASHTO and ASTM standard-based concrete test cylinders. The specimen batches were all uniformly compacted within the cylinders.

The specimen molds containing the concrete samples were placed in WPI's curing room for 28 days. The earthen samples were also placed in the curing room as it was initially unknown of how to appropriately cure these specimens. After two weeks, it was realized that the added moisture from the curing room was not the best method for curing the earthen samples, for the specimens were moister coming out than they were when they were first placed into the curing room. McArleton advised that earthen properties need to not to be cured chemically (i.e. adding moisture), but mechanically (i.e. air drying).

In order to catalyze the process of curing the over-moist specimens, it was decided to allow the larger, six-inch diameter by four-inch tall specimens to be placed in an oven in the WPI laboratory to dry them more quickly. The smaller, three inch diameter by six inch tall specimens were left to air dry for a few weeks in the cylinders before they were removed and exposed to a few fans and a space heater. A few specimens were minimally deformed while taking them out of the cylinders. Specimen 4D, a 10% lime-to-clay plaster sample, broke in half. Every specimen was weighed and photographed for deformities. Overall, the specimens differed in physical appearance because of their compositions (see Figure 9).

Figure 9: All Cylindrical Specimens

3.6. Testing Procedures

After all the specimens were ready, loading, thermal resistivity and vapor permeability tests were conducted in order to study different characteristics of straw bales and renders.

3.6.1. Determining Loading Capacity

In order to evaluate how a plastered-straw bale wall system can withhold compressive, lateral and shear loads, dual-sided plastered bales were placed under such loading conditions in WPI's laboratory to mimic realistic scenarios of loading conditions that apply to actual straw bale structures.

As summarized in Table 4: Configurations of Testing Specimens, 14, three-inch wide by six-inch tall cylinders were prepared to mold the specimen batches for compression testing. This test was intended to provide information on the strength variation of different render recipes, and to control the quality of the mixed renders. However, only 13 specimens were tested because one specimen, 4D, broke. The cylindrical specimens were placed under compressive loads under WPI's *Tinius Olsen* hydraulic universal testing machine to evaluate the compressive strength of each plaster composition. This machine can test in either tension or compression mode. The operating software of this machine was *Instron Partners* software. The maximum loading capacity for this instrument was 400.000lbs.

Four, dual-sided plastered bales were made to test the structural strengths of a plastered-straw bale system. Two bale specimens were configured to experience compression loads (Figure 10), while the other two specimens experienced either lateral or shear loading (Figure 11and Figure 12). The plastered bales were placed on a supported platform and were vertically and uniformly distributed with a ½ inch steel plate. For the shear load test, the platform only supported half of the specimen while the bale was uniformly loaded. By setting up the test in this way, a shear plane was created, as shown in the figure, and the effect of the load on the shear plane was analyzed. For lateral load test the bale was turned so that the load was directly applied to the plastered side of the bale. An unplastered bale was also tested for compression strength so its results could be used to bench mark against the results from the loaded-plastered specimens. Figure 13 shows the actual specimen configurations for the three loading configurations.

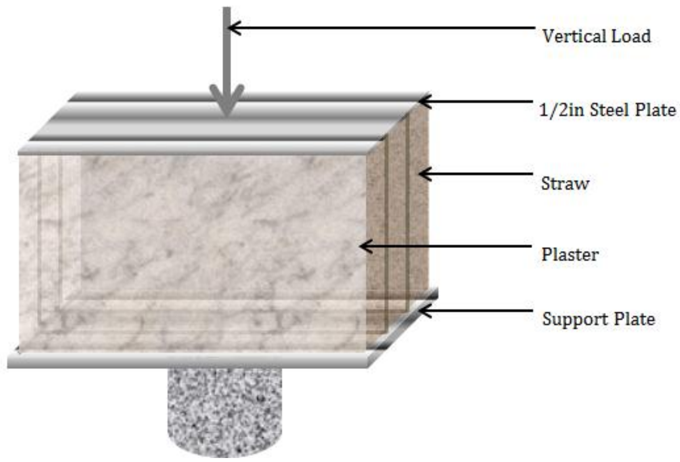

Figure 10: Compression Load Configuration of Dual-Side-Plastered Bale

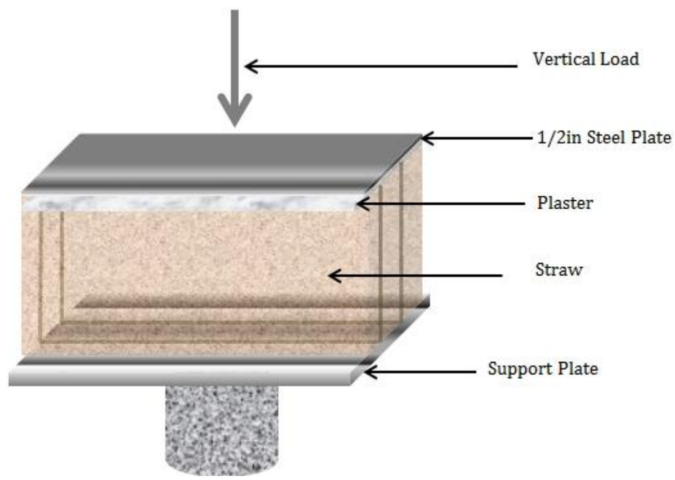

Figure 11: Lateral Load Configuration of Dual-Side-Plastered Bale

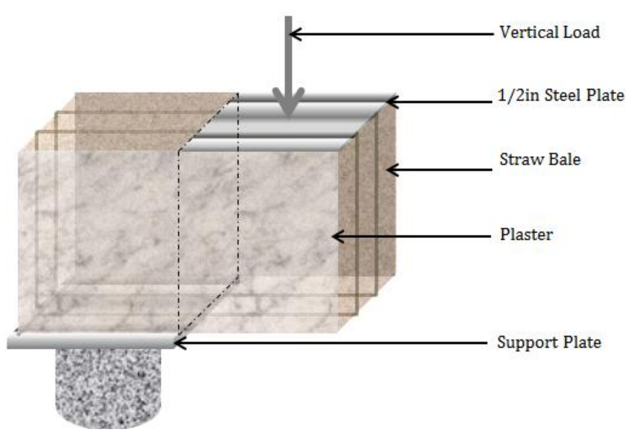

Figure 12: Shear Load Configuration of Dual-Side-Plastered Bale

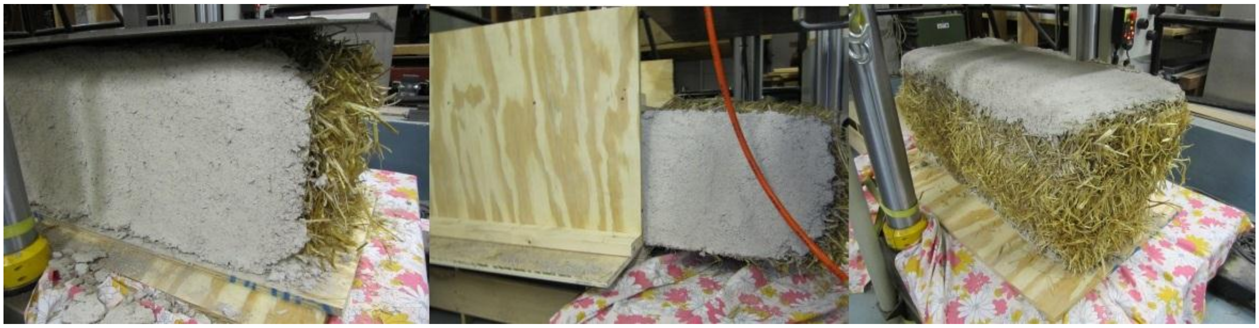

Figure 13: Three Loading Configurations of Plastered-Bale Specimens

The plastered-bale specimens were tested under WPI's *Instron 8803* hydraulic dynamic tester. This machine could be tested in compression, tension or dynamic mode. The operating software used for testing the straw bales was *Instron Merlin* Software. The maximum loading capacity for this instrument was 110,000lbs.

Vertical load was continuously applied for five minutes. Documentation of the testing procedures was taken by video camera. Through the machine's software, load verses displacement diagrams and stress verses strain diagrams were obtained and analyzed to determine compressive and shear strengths of the plastered specimens.

3.6.2. Determining Thermal Resistivity

As summarized in Table 4: Configurations of Testing Specimens, two entirely-plastered bales along with six plaster specimens were tested for thermal resistivity capacities. The test involved the specimens to be probed with thermal couples and be exposed to varying temperatures within WPI's environmental chamber. Data software recorded both the temperature within the chamber as well as the internal temperatures within the specimens to gauge how thermally resistant each specimen was under the environmental conditions. The trend of temperature change over time, the overall temperature change ΔT, and the R-value for each specimen, was collected and analyzed. The R-values were to be calculated by the following equation:

$$R = \frac{\Delta T}{Heat\ Flow\ per\ Unit\ Area}$$

Where: ΔT= change in temperature
Heat Flow per Unit Area= power of environmental chamber/ cross-section area of the chamber
(American Society for Testing and Materials, 2006)

A total of thirteen thermal couplings were used for this test; three per each bale, one for each cylindrical specimen, and one for control. For the cylindrical specimens, one thermal coupling was placed halfway in the specimen, which was approximately three inches deep. For the bale specimens, all three thermal couplings were placed half way down from the height of the bale, which was approximately ten inches, and half way in deep from the width of the bale, which was also approximately ten inches. In terms of spacing, one thermal coupling was placed half way in from the side of the bale, which was approximately 20 inches. The second and third thermal couplings were placed eight and three inches from the side of the bale. Figure 14 shows the setup of the test.

Figure 14: Specimens in Environmental Chamber for Thermal Resistivity Tests

The dimensions of the environmental chamber were approximately ten feet long, by three feet high, by three feet wide. It was determined that the energy needed for powering the environmental chamber was 2000 waltz. The chamber was powered by three individual heaters that could be turned on and off manually at any time and. However, the regularity for the chamber to reach a specific range of temperature in a given time period was uncontrollable. Therefore, it was decided that the best approach to test for thermal resistivity was to set the chamber at its maximum temperature of about 40º C for 28 hours. This time frame would ensure that the thermal couplings would be able reach equilibrium as much as possible. After 28 hours, the heaters were turned off within the chamber, yet the data software still recorded the temperature changes within the specimens for an additional 32 hours as the chamber reached room temperature. This range of temperature change within the chamber, specifically within the given time frame of 60 hours, ensured that the specimens would be exposed to two varying temperature conditions. These conditions provided sufficient, qualitative results regarding the thermal resistivity of the specimens.

3.6.3. Determining Vapor Permeability

As summarized in Table 4: Configurations of Testing Specimens, the water vapor transmission of sixteen plaster specimens were investigated. A falling head permeability test apparatus, as shown in Figure 15, was used to determine the rate of flow of water through six-inch wide by four-inch high cylindrical specimens. From a graduated cylinder, water was allowed to flow through the cylindrical specimens while the interval of time taken to reach a known change in head was recorded. The water level change within the graduated cylinder was recorded every thirty seconds for five minutes. This was done four times for each sample. The average coefficient of permeability, k, of the plaster samples was determined for all rounds of testing using the following equation of Darcy's law:

$$k = \frac{aL}{At} \ln(h_1 / h_2) * t_c$$

"Where: k = coefficient of permeability, cm/s;
a = inside cross-sectional area of the buret, cm^2;
L = average thickness of the test specimen, cm;
A = average cross-sectional area of the test specimen, cm^2;
t = elapsed time between h_1 and h_2, s;
h_1 = initial head across the test specimen, cm;
h_2 = final head across the test specimen, cm.
t_c = temperature correction for viscosity of water; see Tables 1 and 2. A temperature of 20°C (68°F) is used as the standard.
h_1 and h_2 are the dimensions shown in Figure [15] " (Teto, 1999).

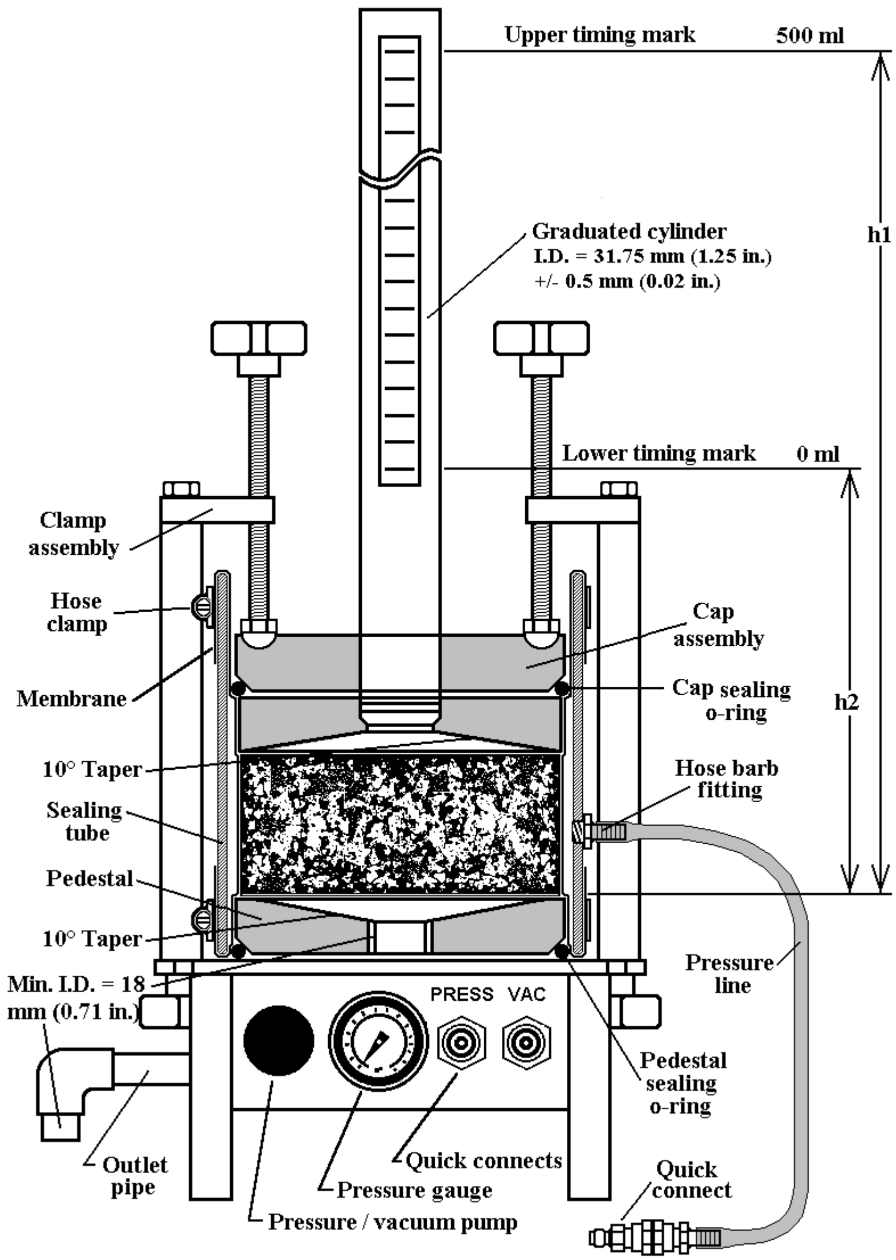

Figure 15: Water Permeability Testing Apparatus (not to scale) (Teto, 1999)

It must be noted, however, that even though there were two cylinders created for each plaster sample, some samples could not be tested due to the fact that they possessed very large voids (e.g. cracks, holes) and were even hindering the performance of the testing apparatus. Even after several attempts to test them, it was concluded for these samples (i.e. 1B, half of 4A, 4B, E1) to not be tested.

3.7. Design of a Straw Bale Structure in Worcester, MA

A one-family, two-story residential structure was both architecturally and structurally designed in compliance by the dimension requirements stated to *780 CMR* to evaluate the applicability of straw bale construction in Massachusetts. Such requirements included story height limits, minimum area of habitable rooms, and minimum opening areas and number of exits. A summary of the dimensional requirements is shown in Table 9.

Table 9: Summary of Limited Dimensions from *780 CMR*

Design Component	Minimum Required Dimension	*780 CMR* Code Reference	Comments
Habitable Area	150 sq. ft.	5304.1 Major habitable Room	Habitable areas include living room, dining room, bedroom, office, family room, etc. Kitchen is excluded.
	70 sq. ft.	*780 CMR*5304.2 Other Rooms	
	Rooms shall be not less than 7 ft. in any dimension	5304.3 Minimum Dimensions	
Emergency Escape Opening	Net clear opening 5.7 sq. ft.	5310.1.1 Minimum Opening Area	At least one must be provided
	20 in by 24 in in either direction	5310.1.2 Minimum Opening Dimensions	
Exit Door	Nominal width 36 in and height 6'-8"	5311.4.2 Exit Door Types and Sizes	At least one must be provided
Interior Door	Doors providing access to habitable rooms: nominal width of 30 inches and height of six feet, six inches		Doors providing access to bath- rooms are permitted to be 28 inches in nominal width.
Stairway	36 inches wide		

When designing without a specific client in mind, the layout was designed to both accommodate the needs of a modern lifestyle and emphasize the unique attributes of the natural construction material. It was deemed favorable to incorporate passive solar lighting and heating to minimize the total energy consumption of the structure, so most windows and the most utilized rooms were designed to face the south side of the building.

Another factor that contributed to the design phase was the thickness of the walls. The thickness of a straw bale wall is dependent on the bale width both interior and exterior plasters. This thickness should range from 16 inches to 24 inches (refer to Appendix E), which is much greater than the exterior walls pertaining to standard construction homes that are typically a maximum of only nine inches. Therefore, the livable interior space of a straw bale structure is more limited than a conventional house of the same outdoor perimeter. In order to maximize living space, it was decided that the shape of the straw bale house should be as simple as possible and should contain a minimum number of corners.

Once the floor plan was developed, a post-and-beam structural system was designed to resist the various loads that would act upon the structure in the area of Worcester, MA. The structural framework was also designed with the floor plan in mind to minimize the impact of space that the framework could occupy. Although there were multiple possibilities of configuring a floor frame plan, a conventional floor frame was utilized, for floor frames can be universally incorporated within a structure, regardless of whether it is a traditional wood-framed structure or a wrap-around straw bale structure.

The *National Design Specifications (NDS)* (American Forest and Paper Association, 2005) was followed to establish the appropriate member sizes for the post-and-beams structure. Various types of design loads, including ground snow load, roof loads and floor live loads, were extracted from *780 CMR*. *780 CMR Table 5301.2. (5)* showed that the ground snow load for the city of Worcester is 40 psf., and *Table 5301.2.(4)* showed that the basic wind speed in Worcester is 90 MPH. These two values were converted to the design snow and wind loads based on ASCE-7 equations, as shown in Appendix E: Structural Analysis of a One-Family, Two-Story Straw Bale Structure in Worcester, MA. *780 CMR Table 5301.5* provided the uniform distributed floor live load to be 40 psf. *780 CMR Table 5301.6* also provided the minimum roof live load for various roof slopes. Since the designed roof slope was a four inch rise for every 12 inches, the roof live load was determined to be 20 psf. Roof and floor dead loads were also estimated by considering the roof framing, insulation, suspended ceiling, roofing, floor covering, partition walls, etc. As most applications of straw bale construction in cold weather climates utilize a wrap-around frame method, the structural members within the design project do not need to support the dead load of the exterior straw bale walls. The detailed calculations of various design loads are presented in Appendix F. Table 10 displays the *780CMR Table 5301.6 Design Roof Live Loads,* and *780 CM R Table 5301.5 Design Live Loads.*

780 CMR TABLE 5301.5
MINIMUM UNIFORMLY DISTRIBUTED LIVE LOADS
(in pounds per square foot)

USE	LIVE LOAD
Attics with storage[b]	20
Attics without storage[b]	10
Decks[e]	40
Exterior balconies	60
Fire escapes	40
Guardrails and handrails[d]	200
Guardrails in–fill components[f]	50
Passenger vehicle garages[a]	50[a]
Rooms other than sleeping rooms	40
Sleeping rooms	30
Stairs	40[c]

For SI: 1 pound per square foot = 0.0479 kN/m^2, 1 square inch = 645 mm^2, 1 pound = 4.45 N.

780 CMR TABLE 5301.6
MINIMUM ROOF LIVE LOADS IN POUNDS-FORCE PER SQUARE FOOT OF HORIZONTAL PROJECTION

	TRIBUTARY LOADED AREA IN SQUARE FEET FOR ANY STRUCTURAL MEMBER		
ROOF SLOPE	0 to 200	201 to 600	Over 600
Flat or rise less than 4 inches per foot (1:3)	20	16	12
Rise 4 inches per foot (1:3) to less than 12 inches per foot (1:1)	16	14	12
Rise 12 inches per foot (1:1) and greater	12	12	12

For SI: 1 square foot = 0.0929 m^2, 1 pound per square foot = 0.0479 kN/m^2, 1 inch per foot = 0.0833 mm/m.

Figure 16: Minimum Design Loads in 780 CMR

Once the design loads were determined, member spacing was decided, and beam, girder and column sizes were chosen from *NDS* for the structural frame design. Various member properties such as the cross sectional area, section modulus, bending strength, and modulus of elasticity were recorded from *NDS* to determine these sizes. The bending strength of the chosen beam size was checked using the method shown in Figure 17. The complete calculation is shown in Appendix F. The same method was used to choose the appropriate girder size with the beam weight added to the floor dead load. The column design process included checking the combined effect of bending and compression forces, as gravity loads typically exert axially on the column and wind forces represent the bending force on the column.

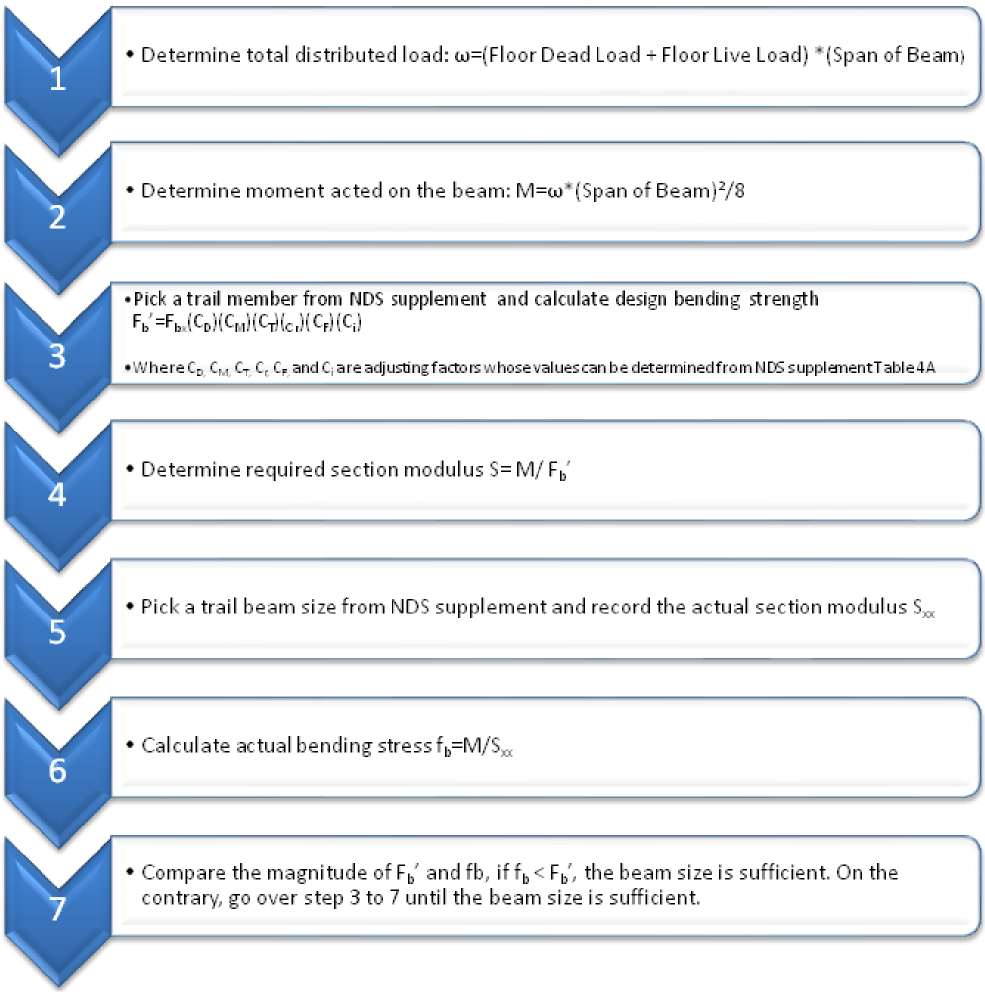

Figure 17: Flow Chart of Choosing Appropriate Member Size

3.8. Cost Analysis

In order to consider the difference in cost between a standard post-and-beam structure and a wrap-around post-and-beam straw bale structure, several calculations and analyses were conducted. Literature findings from *RS Means Square Foot Costs (2008)* were used to acquire a list of costs for specifications (i.e. site work, foundations, finishes, etc.) of a standard-built residential structure. Conveniently, *RS Means* provided a list of costs for all features within a standard model home in terms of dollars per square foot. A summary of a standard model home's features that had listed costs in the *RS Means* can be viewed in Table 10.

Table 10: Details of Standard House

Division:	Feature:
01: General Requirements	General contractor overhead and profit
02: Site Construction	Lower level excavation/site preparation for slab; 4' deep trench excavation for foundation wall
03: Concrete	Continuous reinforced concrete footing, 8" deep x 18" wide; dampproofed and insulated 8" thick reinforced concrete foundation wall, 4' deep; 4" concrete slab on 4" crushed stone base and polyethylene vapor barrier, trowel finish.
04: Masonry	4" crushed stone base
05: Metals	Aluminum gutters, downspouts, drip edge and flashings
06: Wood and Plastics	Post and beam frame; Log exterior walls
07: Thermal and Moisture Protection	Dampproofed and insulated 8" thick reinforced concrete foundation wall
08: Doors and Windows	Double hung windows; 3 flush solid core wood exterior doors with storms; hollow core and louvered interior doors.
09: Finishes	Gypsum wallboard, walls and ceilings- ½" taped and finished drywall, primed and painted with two coats; painted base boards and trim, finished hardwood floor 40%, carpet with ½" underlayment 40%, vinyl tile with ½" underlayment 15%, ceramic tile with ½" underlayment 5%; 25 year asphalt shingles; #15 felt building paper
10: Specialties	1 lavatory, white, wall hung; 1 water closet, white; 1 bathtub, enameled steel, white;
11: Equipment	40 gallon electric water heater; gas fired warm air heat; 100 Amp. Service; romex wiring; incandescent lighting fixtures, switches, receptacles.
12: Furnishings	Average grade kitchen cabinets-14 L.F. wall and base with plastic laminate counter top and kitchen sink
10: Additional Specialties	Additional full bath
	Half bath

(RSMeans, 2007)

However, as straw bale structures do incorporate such unique components, *RS Means* did not supply the costs of each straw bale home feature. Therefore this had to be done manually. It was essential to incorporate as many similar features within the straw bale home that was a part of the model home in order to provide an accurate cost analysis between the two structures. In doing this, it would be assured that any cost difference between the structures would due to dependent variables (e.g. dry wall, plasters) of the structure and not on independent variables (e.g. specialties, furnishings). A summary of the features that were selected to be presented in the straw bale home cost analysis can be viewed in Table 11.

Table 11: Details of Straw Bale House

Division:	Feature:
01: General Requirements	General contractor overhead and profit
02: Site Construction	Excavation and fill, 4' sand, gravel or common earth, on site storage
03: Concrete	Slab on grade foundation, 4" thick, non-industrial, non-reinforced
04: Masonry	Plaster
05: Metals	Gutters and Downspouts
06: Wood and Plastics	2"x 4" Fink (roof) Truss "W" with 24" o.c.
	3" x 8" beams
	8 ¾" x 9" columns (used 6" x 10" columns for pricing)
	8" x 12" girders (used 2" x 12" girders for pricing)
	2" x 4" "Exterior" Frame
07: Thermal and Moisture Protection	Exterior walls (Straw Bale Walls including installation and plastering)
08: Doors and Windows	36"x 84" interior doors (used 36" x 80" doors for pricing)
	42" x 84" exterior doors (used 36" x 80" exterior doors for pricing)
	Single hung 3' x 4' windows
09: Finishes	Gypsum wallboard
	Finished oak, ¾" x 2 ¼" select grade-red wood flooring 40%, nylon level loop with 3/8" nova pad 20 oz. carpet 40%, themes series 0.08 thick 2.9 performance appearance ratings in beige cameo vinyl flooring 15%, glazed floor tile ¼" thick better quality patterns 5%
	#15 felt underlayment for roof
	Job-built stairway
10: Specialties	2 full baths
	1 half bath
11: Equipment	40 gallon electric water heater
	Electrical
12: Furnishings	Kitchen sink
	Kitchen countertops with 14 L.F.
	Kitchen cabinets
	Lighting fixtures

(RSMeans, 2002), (Pray, 2009), (RSMeans, 2008), (RSMeans, 1996), (McArleton & Racusin, 2010)

In order to further ensure that the features between the structures were as similar as possible, additional specialty features needed to be added to the cost list of the standard home as *RS Means* only incorporated one full bath into the given cost analysis whereas the designed straw bale home incorporated two full baths and one half bath. Overall, the cost of all the features for each structure was analyzed in regards to 1200 sq. ft. of area.

It must be noted that the resources used to gather the data for this cost analysis incorporated various costs over a time span of different years. In order to account for the difference in cost in terms of inflation from each passed year from the current market price, 3% of cost increase was factored into the final cost estimate of each analyzed feature cost. The location factor cost for Worcester, MA was also added to each total cost. An additional 20% markup cost was appended to the final total costs for each structure. A cost comparison between the two structures was then conducted.

4. Results and Analysis

This section contains the results of various plaster components and straw bale specimen configurations in terms of vapor permeability, thermal resistivity, and compression strength. The results were analyzed in order to assess the correlation of these systems and how applicable they can be relative to cold climate regions.

4.1. Loading Tests

During the test process, both plastered and unplastered bales exhibited elastic deformation and demonstrated strong structural strength. The test for the unplastered bale ended when the bale was deformed to the maximum extent of how far the head of the *Tinius Olsen* machine could extend; five inches. For the plastered bales, the tests were concluded after 1.5 inches of deformation, and the plaster began cracking and falling off excessively at around .75 inches of deformation. Table 12 summarizes the maximum load capacity of the test specimens under different loading conditions. For graphs that were produced by *Instron Partners* software, refer to Appendix G: Compressive Bale and Specimen Test Results (Printed Graphs).

Table 12: Compression Test Results of Bales

Maximum compressive load for unplastered bale	Maximum compressive load for plastered bale	Maximum lateral load for plastered bale	Maximum shear load for plastered bale
6250 lb./ ft.	1600 lb./ ft.	3500 lb./ ft.	4921 lb./ ft.

Figure 18 shows how much force in LBF that a plastered bale can withstand in comparison to an unplastered bale. Even though the dual-sided-plastered bale underwent a lateral loading, it shows that the plaster added significant strength to the overall loading capacity of the bale. Under the same deformation, the plastered bale was able to withstand over 6,000 LBF while the unplastered bale only withheld a little over 3,000 LBF. This data was extracted from the *Instron Partners* software and was manipulated in Microsoft Excel.

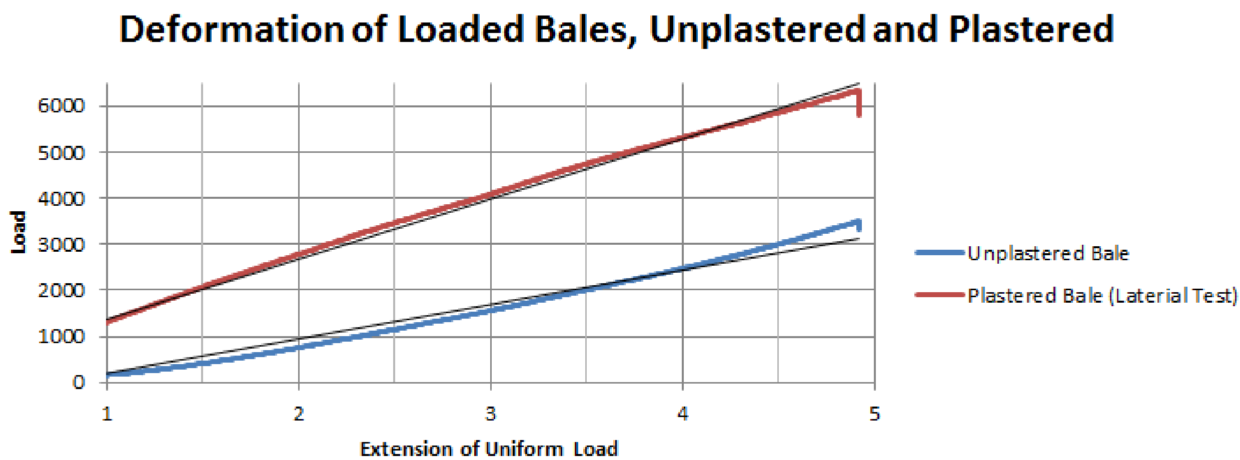

Figure 18: Deformation of Loaded Bales in PBF

The four configurations that were tested for the earthen-based plaster specimens included a lime-and-sand based plaster, a 10% manure-to-mix batch, a 25% manure-to-mix batch, a 40% manure-to-mix batch, and an earthen-control sample. Note that the earthen-control specimens incorporated two samples of two separate batches of the same mix configuration. In terms of the compressive tests for the plaster cylinders, the results of all specimens were manipulated in Microsoft Excel and are shown in Figure 19.

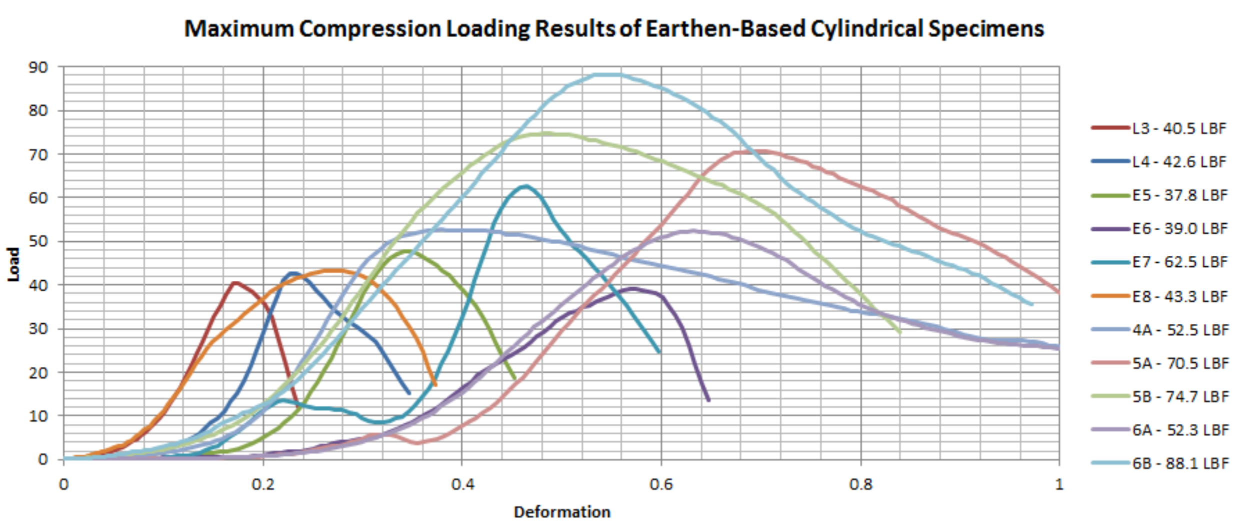

Figure 19: Compression Loading of Earthen-Based Cylindrical Specimens

For the lime-and-sand plaster specimens, L3 and L4, stress was applied to the first sample and the maximum load that the specimen could withstand was 40.46 psi whereas the second sample withstood a load of 42.58 psi. As these results supplied similar strengths, it can be assumed that the lime-and-sand specimens were tested with minimal voids. However, the earthen-control plasters differed as they took dissimilar sustained maximum loads of 47.82 psi and 39.05 psi from the first batch (E5 and E6) 63.53 psi and 43.29 psi (E7 and E8). As average maximum loads of the earthen-control specimens were 48.41 psi, it can be deduced that earthen-based plasters are stronger than lime-and-sand based plasters. However, it must be noted that the main function of lime-and-sand plasters is for the use as a final coating to prevent weathering, and not to produce high structural strength.

The compression tests regarding the varying manure-to-mix ratios showed that the plasters with higher ratios of manure were able to withstand higher compressive loads. One 10% manure-to-mix sample, 4A, was tested, as 4B broke during preparation. 4A tested to have a peak load of 52.49 psi. However, for the sample s with 25% manure-to-mix, 5A and 5B, they withstood loads of 70.45 psi and 74.70 psi. The samples with 40% of manure-to-mix, 6A and 6B, held loads of up to 88.28 psi and 52.36 psi. Even though these results vary within configurations, and that a limited number of specimens were tested per each configuration, it can be deduced that the addition of manure to a mix does increase the compression strength of an earthen-based plaster as all the maximum loads of the high manure content specimens were higher than the average compression strength of the earthen-based plasters.

As concrete is such a widely used material, lime-and-cement-based plaster specimens were also tested and analyzed in comparison to the earthen-based specimens. These samples, C5 and C6, had the maximum compression load capacities of 2,835 psi and 2,858 psi. Refer to Appendix G: Compressive Bale and Specimen Test Results (Printed Graphs) for all graphs.

4.2. Thermal Resistivity Tests

Two entirely-plastered bales, encased in either the lime-and-cement-based plaster or the earthen-control plaster, along with six cylindrical plaster specimens, consisting of lime-and-sand, earthen-control, and lime-and-cement plasters, were tested for their thermal resistivity capacities. The specimens were probed with thermal couplings and were exposed to several temperature changes in WPI's environmental chamber for duration of 60 hours. The data software recorded the temperature changes within the test specimens over the 60 hour period and the data was manipulated in Microsoft Excel. Table 13 shows the total temperature changes within the plastered bales and cylinders in relation to the ambient temperature of the environmental chambers for both heating and cooling conditions.

Table 13: Summary of Temperature Changes of Thermal Resistivity Testing Samples

Thermal Coupling Placement (inches)		Coupling No.	ΔT (Cº) during Heating (28 hr.)	ΔT (Cº) during cooling (32 hr.)	ΔT (Cº) overall (60 hr.)
Concrete Bale	22 x 10 x 10	1	3.40	3.18	6.58
	8 x 10 x 10	2	3.84	2.41	6.26
	3 x 10 x 10	3	6.77	-1.28	5.49
Earthen Bale	22 x 10 x 10	4	5.05	1.70	6.75
	8 x 10 x 10	5	4.83	1.63	6.47
	3 x 10 x 10	6	10.72	-5.12	5.60
Concrete Cylinder	3	7	14.11	-9.58	4.53
	3	8	14.07	-9.45	4.60
Earthen Cylinder	3	9	13.22	-10.82	2.41
	3	10	12.65	-10.44	2.21
Lime Cylinder	3	11	12.35	-10.14	2.21
	3	12	14.31	-12.19	2.11
Control (Ambient)		13	17.13	-14.54	2.59

According to the Table 13, where there is greater temperature change between the temperatures of the various locations of the specimens and the ambient temperature, it can be indicated that there was poor thermal resistivity for that heating or cooling period. For both heating and cooling periods, more temperature change occurred in the cylindrical samples as opposed to the bale specimens.

Figures 20 - 26 show the overall trends of temperature changes of the specimens throughout the duration of the test. Based on all of these figures, it can be deduced that the specimens that experienced the least amount of temperature change in regards to the ambient temperature were the most thermally resistant. Generally speaking, the least amount of temperature change occurred within the earthen-plastered bales. This demonstrates that earthen-based plasters are more thermally resistant than lime-and-cement plasters when applied onto bales. This is apparent for all the different locations with the bales that the thermal couplings were placed in. This trend can be seen in Figures 20 – 25.

This data also infers that the plaster itself does not act as the main thermal insulator within a plastered-straw bale system. Looking at the results from the various placements of the thermal couplings within the bales, it is apparent that the difference of temperature change between the thermal couplings and the ambient temperature reduces between the couplings that were probed in the middle of the bale in regards to those that were probed closer to the surface of the bale. See Figures 23, 24 and 25.

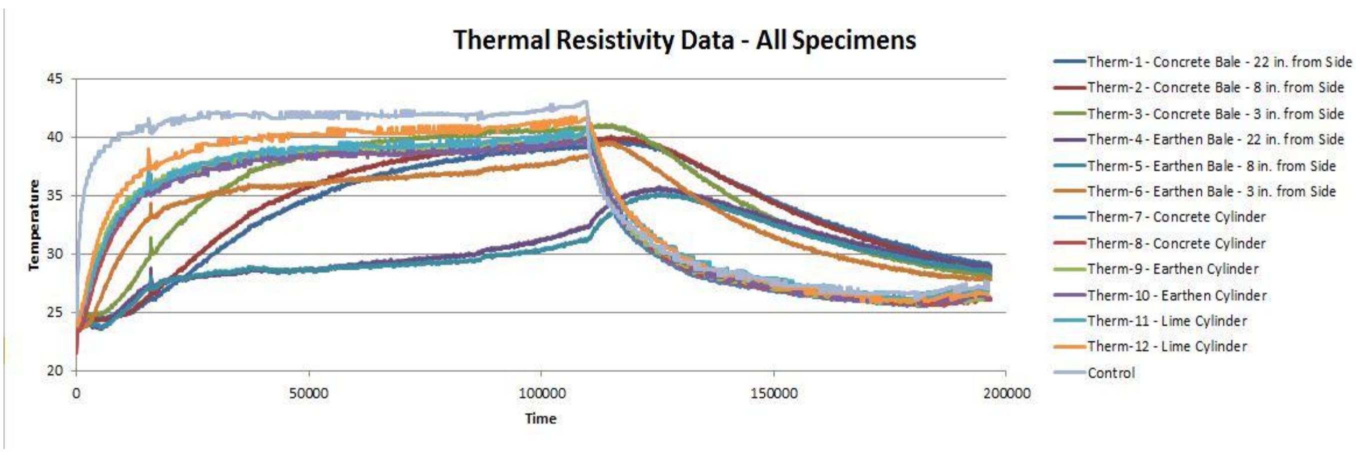

Figure 20: Thermal Resistivity Data of All Tested Specimens

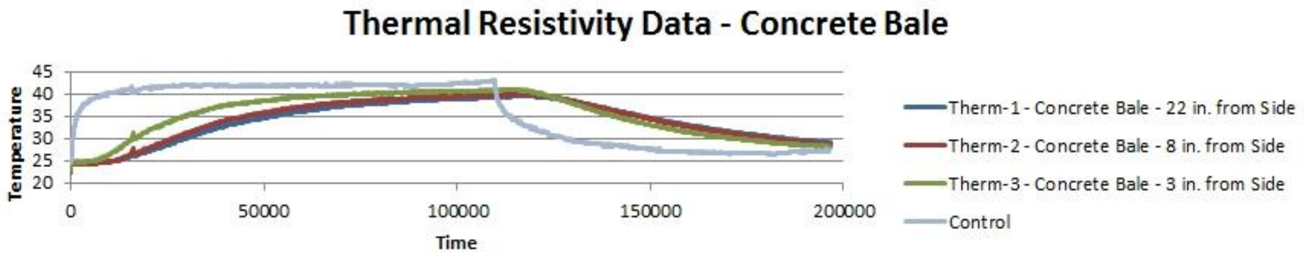

Figure 21: Thermal Resistivity Data of Concrete Bale

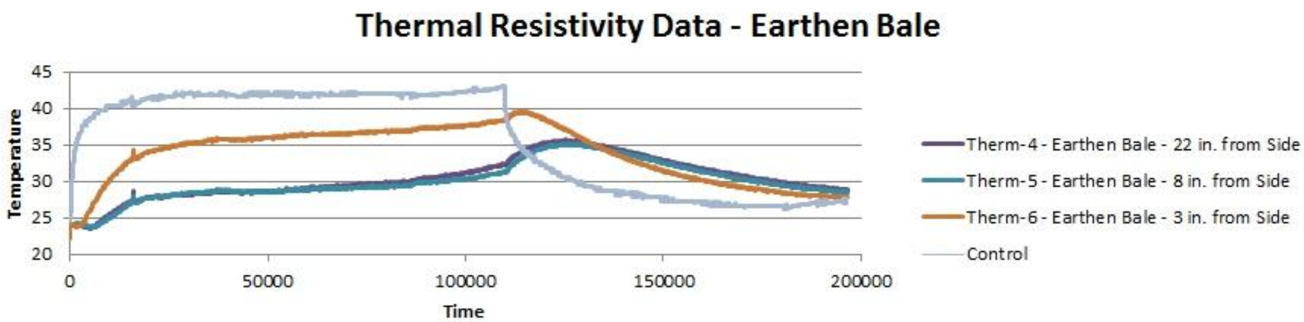

Figure 22: Thermal Resistivity Data of Earthen Bale

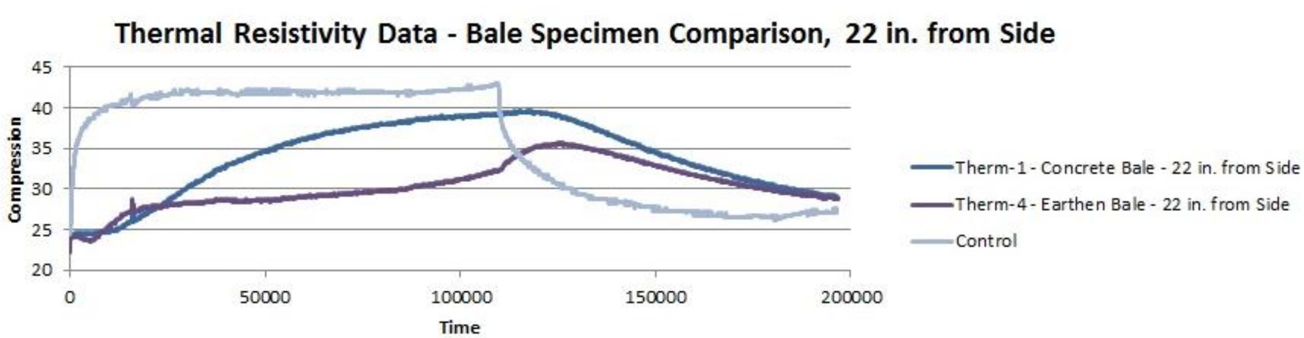

Figure 23: Thermal Resistivity Data of Bales, 22in. from Side

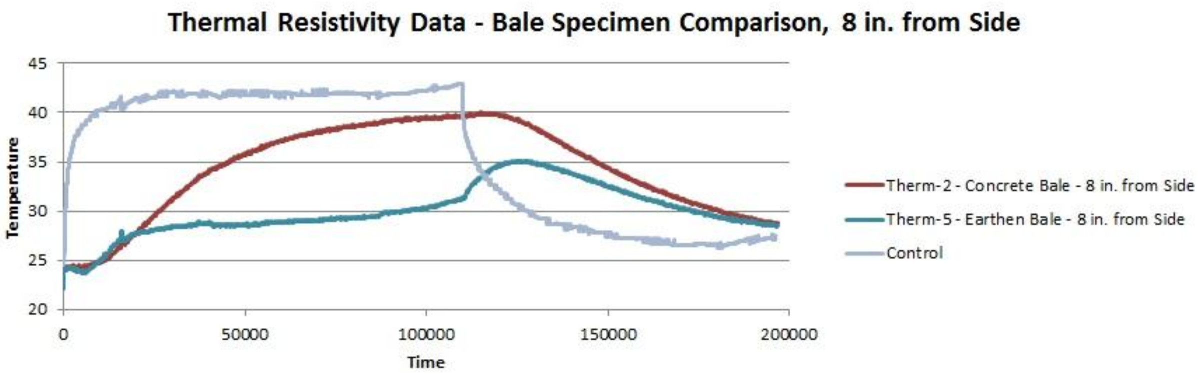

Figure 24: Thermal Resistivity Data of Bales, 8 in. from Side

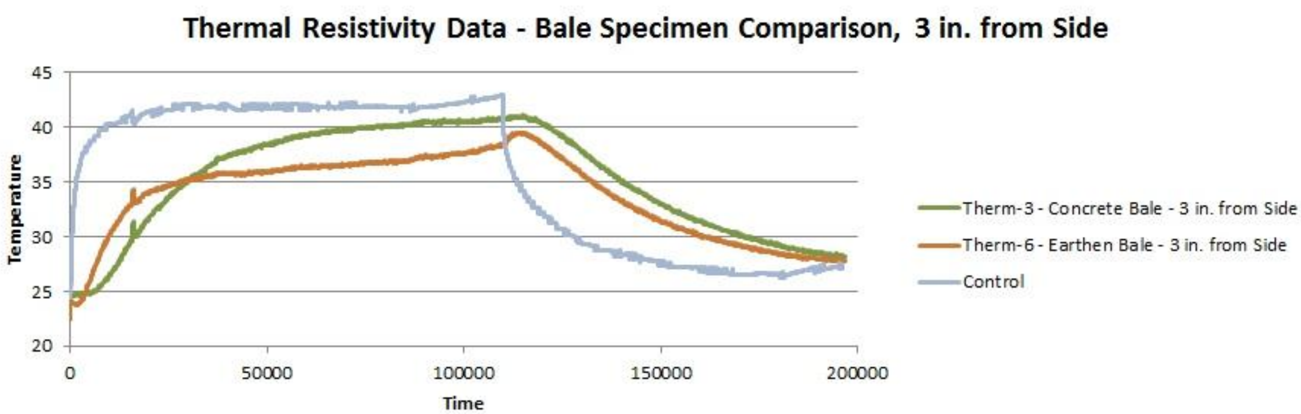

Figure 25: Thermal Resistivity Data of Bales, 3 in. from Side

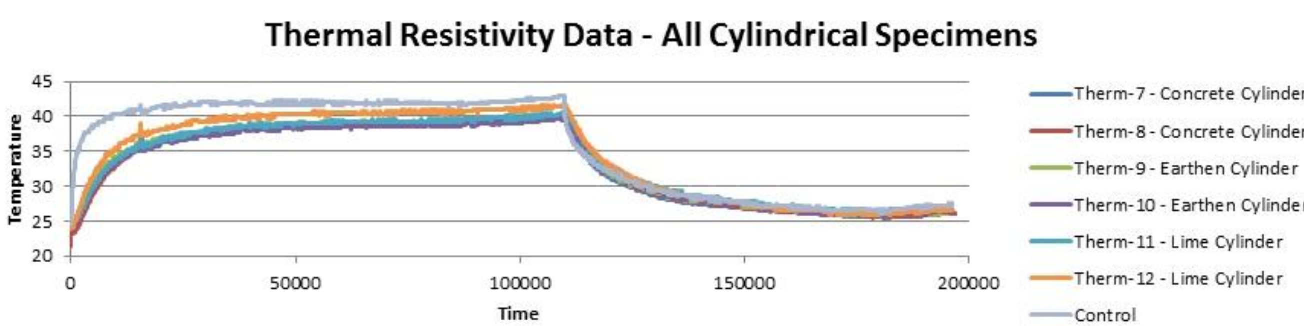

Figure 26: Thermal Resistivity Data of Cylindrical Specimens

Figure 26 specifically shows the trend of the temperature changes in the cylindrical specimens. It can be deduced from both this figure, and Table 13, that the temperature change in the lime-and-cement samples was less than that of the earthen-control and lime-and-sand samples. This indicates that there is a higher thermal resistivity in cement-based plasters individually. However, this change in temperature is very minimal in regards to the entire spectrum of data. In addition, as deduced previously, the thermal efficiency of a plastered-bale wall is not dependent on the plaster, but on the bale. Accordingly, the thermal resistivity difference between cement and earthen-based plasters was more prominent when accorded with bales. Therefore, it can still be deduced that earthen-based plasters are more thermally resistant than cement-based plasters. The lime-and-sand-based specimens were shown to be the least thermally efficient in terms of all the cylindrical specimens. Overall, it can be deduced that the cylindrical samples were less thermally efficient because they were composed of less mass than the bales, and because the great density of the straw bales could have eliminated the amount of air in which temperature could pass through.

To further quantify how thermally efficient the plastered bales were, the R-value, or the thermal resistivity per inch of specimen, was determined by the following equation:

$$R = \frac{\Delta T}{Heat\ Flow\ per\ Unit\ Area}$$

Where:
ΔT= change in temperature
Heat Flow per Unit Area= power of environmental chamber/cross-section area of the chamber
(American Society for Testing and Materials, 2006)

In order to determine the R-value of the plastered-bale specimens, it was deemed favorable to evaluate the location of the specimens where the most prevalent thermal resistivity occurred within the data spectrum. Therefore, the heating value changes from where couplings were placed 22 inches deep were used as the ΔT for the equation. Based on the specifications of the environmental chamber, as described in Section 3.6 Testing Procedures, it was determined that the Heat Flow per Unit Area of the chamber equaled 0.46 W/in^2

when 2000 waltz was divided by 4320 in^2. Using these values, the R-value for the two bales were then calculated and presented in Table 14.

Table 14: R-values for the Two Plastered Bales

Thermal Coupling Placement (inches)		Coupling No.	ΔT (Cº) during Heating (28 hr.)	Heat Flow per Unit Area (W/in^2)	R-value (per inch)
Concrete Bale	22 x 10 x 10	1	3.40	0.46	7.39
Earthen Bale	22 x 10 x 10	4	5.05		10.97

In compliments to the other deductions that are mentioned in this section, it is apparent that the R-value of the earthen-plastered bale is greater than that of the concrete-plastered bale. Generally speaking, these calculations are similarly comparable to other straw bale evaluations to date that report the R-value of bales ranging from 5.2 to 10.8 per inch.

4.3. Vapor Permeability Tests

Testing for vapor permeability within plasters was essential to determine how breathable straw bale structures can be. It is essential for vapors to continuously transfuse in and out of plastered bale walls in order to ensure qualitative air content within the structure, as well as avert moisture from accumulating within the bale walls. As plaster is such a critical component of straw bale structures, seven different configurations of plasters were tested for their vapor permeability capacities. This included the fiber reinforced-lime-and-cement plaster, the earthen-control plaster, the 10%, 30%, and 50% lime-to-clay plasters, and the 10%, 25%, and 40% manure-to-mix plasters.

The two fiber reinforced-lime-and-cement plaster samples, specimens C1 and C2, performed negligible permeability because no water transmission was observed within the two samples whatsoever. Therefore, it was deduced that cement-based plasters are impermeable. Accordingly, it was deduced that cement-based plasters would not be applicable for straw bale construction in cold-climate regions because of the excessive rain and moisture that cold-climate regions do exhibit. Additionally, because the cement-based samples were entirely impermeable, they were regarded as moot specimens and were neglected to be compared with the other earthen-based samples in the forthcoming data manipulations.

The earthen-based specimens, on the other hand, did experience some vapor permeability abilities within testing. However, It must be noted that the apparatus (refer to Figure 15) used for this test was very faulty and temperamental. For example, the pressure value of the apparatus was unstable and had to be frequently pumped manually. Generally speaking, it is probable that many of the test results were compromised as it was difficult to simultaneously add water, time the difference between head, and stabilize pressure within the system to conduce accurate results. In order to balance out all of the factors, four rounds of tests were conducted for each tested specimen. However, only two rounds of tests were conducted for specimen 4A due to some miscalculations during testing.

A summary of all the vapor permeability capacities for each specimen, as quantified by the calculated k values, can be seen in Table 15. The higher the coefficient of permeability, k , value was calculated, the more vapor permeable a specimen was. Note that specimens 1B, 4B, and E5 were not tested due to voids. The data that was used to calculate the k values can be viewed in Appendix H. The calculations of the k values themselves can be viewed in Appendix I.

Table 15: Cylindrical Specimens with and their Coefficients of Permeability

Cylindrical Specimen:	Average Coefficient of Permeability, k (in. /min.)
1A (Earthen with 10% lime-to-clay)	0.0045
1B (Earthen with 10% lime-to-clay)	Could not be tested
2A (Earthen with 30% lime-to-clay)	0.010
2B (Earthen with 30% lime-to-clay)	0.039
3A (Earthen with 50% lime-to-clay)	0.062
3B (Earthen with 50% lime-to-clay)	0.086
4A (Earthen with 10% manure-to-mix)	0.010
4B (Earthen with 10% manure-to-mix)	Could not be tested
5A (Earthen with 25% manure-to-mix)	0.019
5B (Earthen with 25% manure-to-mix)	0.0033
6A (Earthen with 40% manure-to-mix)	0.036
6B (Earthen with 40% manure-to-mix)	0.0084
E5 (1^{st} control batch)	Could not be tested
E6 (1^{st} control batch)	0.0031

After finding the *k* values for all the tested specimens, it is apparent that the *k* values widely differed amongst and between specimen configurations. Again, this it can be deduced that these numbers were so variable because of the unreliability of the testing apparatus and due to the complications that were apparent during testing. For example, there is a stark different of *k* values between specimens 6A and 6B, which both are made of the same sample batch; 40% manure-to-mix. 6A's *k* value is 0.036 in. /min., which is a relatively high value, whereas 6B's value was 0.0084 in. /min., which is a relatively low vapor permeability rate in comparison to all the other specimen values. The great difference of *k* values between 5A and 5B also shows to be peculiar. Consequentially, it remains difficult to deduce whether or not manure increases or decreases the permeability of a plaster because the test results of this project show both variations of increase and decreases in terms of the manure-to-mix spectrum. From 4A to 5A, there is an increase in permeability, yet there is a decrease from 4A to 5B. Additionally, there is an increase in permeability to 6A, yet a decrease to 6B.

Nevertheless, even though limited and highly-voided data was acquired, some trends were formulated from the data that was acquired. In terms of the lime-to-clay-based samples, it can be presumed that a higher portion of lime increases the vapor permeability of a plaster. In addition, aside from the fact that the values of the manure-to-mix specimens seem to be a stark outliers, it can be inferred that an increase in manure might increase permeability as well. However, it can be deduced that higher concentrations of lime do in fact make a plaster more vapor permeable as opposed to any greater concentrations of manure. However, when observing the *k* values of the earthen-control batch, E6, it can be distinguished that out of all samples tested, this configuration was the least permeable. Grant it, that even though only one specimen of this configuration was tested, and that all of these test results seem to be very erratic, it is peculiar to see that this configuration did produce a low *k* value as this specimen's composition of ingredients combined very similar portions to the highly permeable lime-to-clay and manure-to-mix specimens.

4.4. Straw Bale House Design

The applicability of straw bale construction was evaluated in terms of its constructability, environmentally-friendly aspects, sustainability, and health and safety aspects. Using literature findings and consultation advice, a realistic architectural and structural design of a straw bale structure was created in order to evaluate the ability of a straw bale structure to abide to *Massachusetts State Building Codes*. This entailed determining the structural performance of a designed one-family, two-story wrap-around-frame straw bale structure that was integrated with environmentally-friendly design principles.

First and foremost, floor plans of a straw bale home were designed and integrated with environmentally-friendly, as well as modern-lifestyle fitting design principles. The main components of the first floor plan included a kitchen, dining area, and living space. Short length interior walls were included in the design to indicate the separation of different rooms while maintaining an open and flexible space. A double hung door was designed to be located in the middle of the living area where the backyard could be accessed. The design also incorporated several windows to accommodate as much natural lighting as possible to minimize electricity consumption and to give the room an open and spacious feeling, as shown in Figure 27.

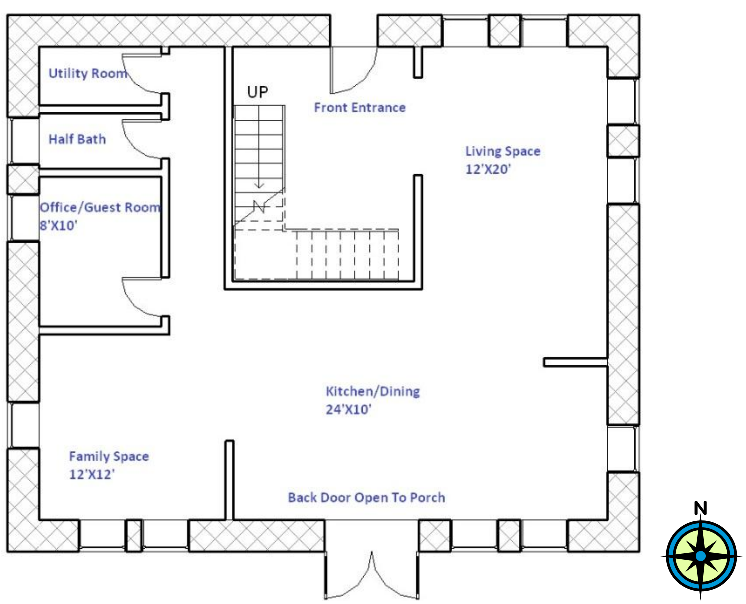

Figure 27: Design of First Floor Plan for Straw Bale House

The stairs that lead to the second floor were placed in front of the main entrance to produce a uniform circulation path and minimize the amount of space taken away from the living area. Accordingly, in order to maximize spaciousness, the ceiling for the first floor entrance was extended to reach the ceiling of the second floor. The master bedroom was located at the opposite end of the stairs to provide privacy and was designed to be approximately 176 square feet, which is within the typical range of 168 to 384 square feet for master bedrooms (*Architectural Design Standards*, 2007). A master bathroom and walk-in closet, which have become prominent features in modern homes, were also incorporated in the design. The master bathroom was designed to be 60 square feet of area, which is within the average range of a full bathroom of 54 to 96 square feet (*Architectural Design Standards*, 2007), as shown in Figure 28.

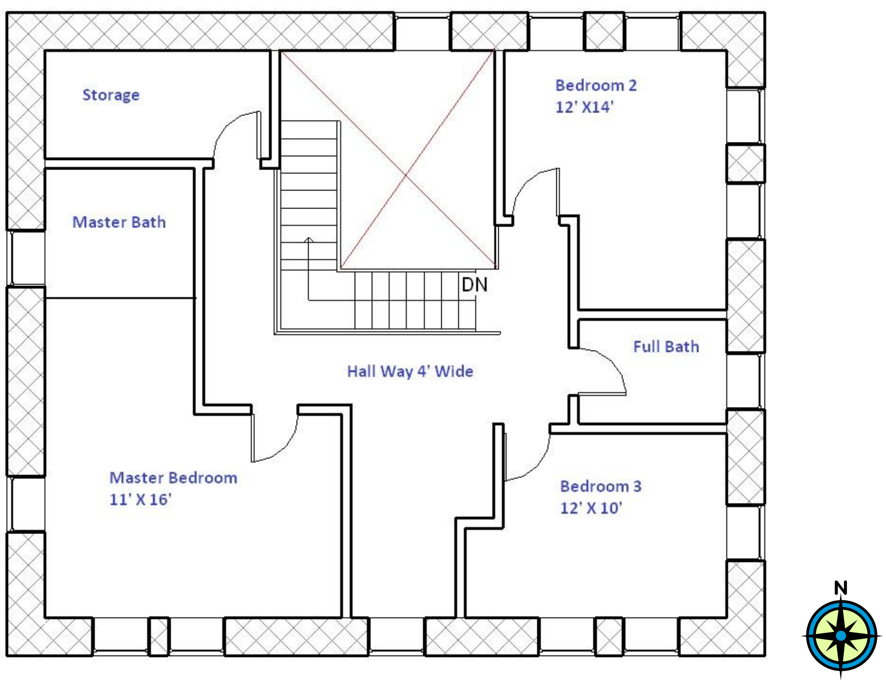

Figure 28: Design of Second Floor of Straw Bale House

Nowadays, there is a popular desire in current modern homes to have two bedrooms in addition to a master suite as most American families have two children (U.S. Census, 2000). Consequentially, it was decided to incorporate two secondary bedrooms into the design so that each child could have its own room. The bedrooms were designed to have an area of about 130 square feet, which is within the standard limits of 100 to 224 square feet for a bedroom (Architectural Graphic Standards, 2007). A second full bathroom was designed to be in between the bedrooms for convenience. A loft space was also designed for the second floor to accommodate diverse activities.

A structural floor was designed as a post-and-beam structural frame as shown in Figure 29. Beam sizes were designed to be 3" x 8" x 15' spaced 1.5 feet on center, girder sizes were designed to be 8" x 12"x 12' spaced 15 feet on center, and column sizes were determined to be 8.75"x 9" x 18'. All of these structural components were designed to be composed of a Douglas Fir Select Structure wood type and were all chosen from the *NDS* Supplement.

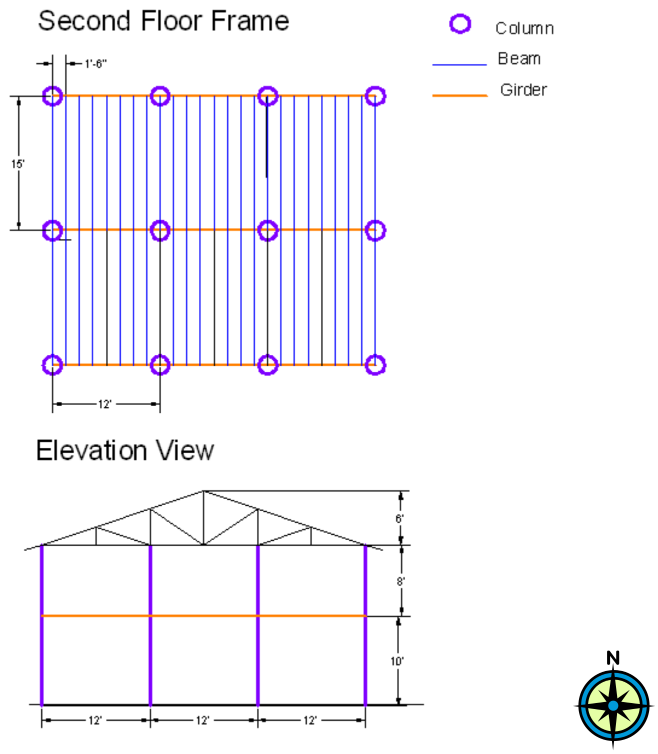

Figure 29: Structural Plans for the Designed House

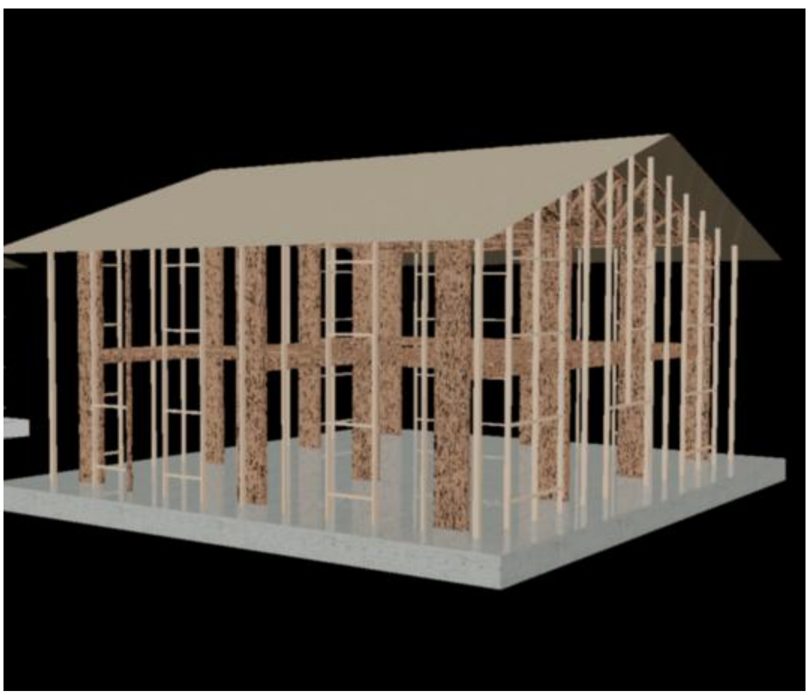

Figure 30: An AutoCAD Render of the Structural Frame

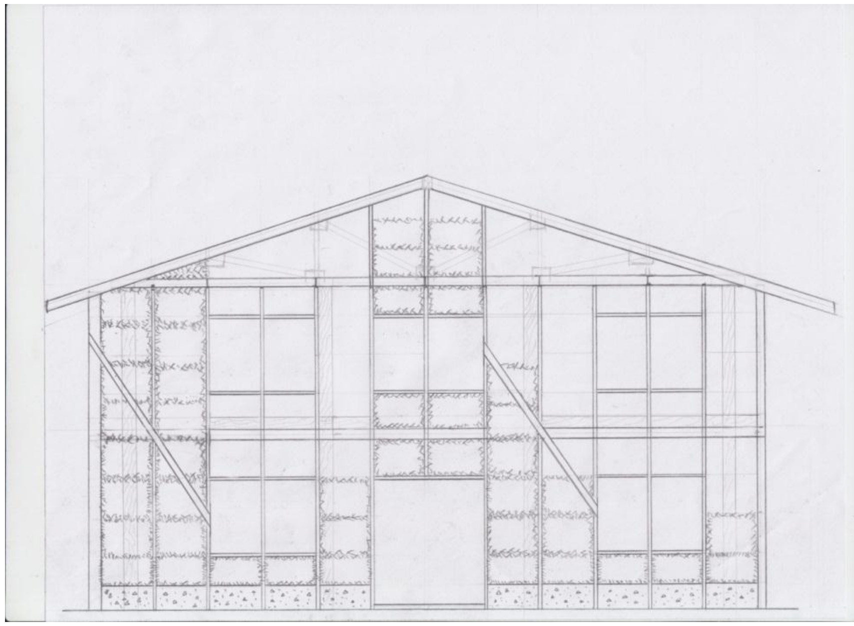

Figure 31: Elevation View of the Design House in Construction

Figure 30 is an illustration of the designed structural frame and exterior non-loading bearing frame that is specifically used for supporting windows and doors (Appendix D). Figure 31 is an elevation view of the designed house in a mid-construction illustration. For construction, the bottoms of the first courses of bale were supported with concrete blocks and plywood as a required specification of keeping bales at least 16 inches above the finish grade (refer to Section 2.3 Relationship with Other Construction Material Elements). Bracing was also used for the exterior frame for lateral stability.

Overall, designing the structural post-and-beam frame for the straw bale structure was simple as the floor layout incorporated a simple design and the process of following the structural design criteria and standards presented in *780 CMR* and *NDS* documents was straightforward.

4.5. Cost

In order to differentiate the cost effectiveness of constructing with straw bale, a cost analysis between a standard post-and-beam house and a wrap-around-post-and-beam straw bale house was conducted. Based on the references of *RS Means* literature and on the consultation of McArleton and Racusin, the total costs of both construction methods were obtained. A summary of the costs is shown in Tables 16 and 17.

Table 16: Cost Analysis Breakdown for an "Average" Post and Beam House (1200 sq. ft.)

Division:	Feature:	Cost ($):
01: General Requirements	General contractor overhead and profit	
02: Site Construction	Lower level excavation/site preparation for slab; 4' deep trench excavation for foundation wall	
03: Concrete	Continuous reinforced concrete footing, 8" deep x 18" wide; dampproofed and insulated 8" thick reinforced concrete foundation wall, 4' deep; 4" concrete slab on 4" crushed stone base and polyethylene vapor barrier, trowel finish.	
04: Masonry	4" crushed stone base	
05: Metals	Aluminum gutters, downspouts, drip edge and flashings	
06: Wood and Plastics	Post and beam frame; Log exterior walls	
07: Thermal and Moisture Protection	Dampproofed and insulated 8" thick reinforced concrete foundation wall	
08: Doors and Windows	Double hung windows; 3 flush solid core wood exterior doors with storms; hollow core and louvered interior doors.	
09: Finishes	Gypsum wallboard, walls and ceilings- ½" taped and finished drywall, primed and painted with two coats; painted base boards and trim, finished hardwood floor 40%, carpet with ½" underlayment 40%, vinyl tile with ½" underlayment 15%, ceramic tile with ½" underlayment 5%; 25 year asphalt shingles; #15 felt building paper	
10: Specialties	1 lavatory, white, wall hung; 1 water closet, white; 1 bathtub, enameled steel, white;	
11: Equipment	40 gallon electric water heater; gas fired warm air heat; 100 Amp. Service; romex wiring; incandescent lighting fixtures, switches, receptacles.	
12: Furnishings	Average grade kitchen cabinets-14 L.F. wall and base with plastic laminate counter top and kitchen sink	
		122160.00
10: Specialties Additional	Additional full bath	5129.00
	Half bath	3107.00
		Total Cost=130396.00
		Final Cost (including year differences, location factor, labor and markup) = **195,235.41**

(RSMeans, 2007) *(Please refer to Appendix F: Cost Estimation Analysis for more detailed calculations and features)*

Table 17: Cost Analysis Breakdown for the Straw Bale House (1200 sq. ft.)

Division:	Feature:	Cost ($):
01: General Requirements	General contractor overhead and profit	29441.56
02: Site Construction	Excavation and fill, 4’ sand, gravel or common earth, on site storage	984.00
03: Concrete	Slab on grade foundation, 4” thick, non-industrial, non-reinforced	3852.00
04: Masonry	Plaster	(included in the price of Thermal and Moisture Protection)
05: Metals	Gutters and Downspouts	306.12
06: Wood and Plastics	2”x 4” Fink (roof) Truss “W” with 24” o.c.	4471.20
	3” x 8” beams	2050.00
	8 ¾” x 9” columns (used 6” x 10” columns for pricing)	3725.00
	8” x 12” girders (used 2” x 12” girders for pricing)	1100.00
	2” x 4” “Exterior” Frame	1096.00
07: Thermal and Moisture Protection	Exterior walls (Straw Bale Walls including installation and plastering)	47736.00
08: Doors and Windows	36”x 84” interior doors (used 36” x 80” doors for pricing)	617.80
	42” x 84” exterior doors (used 36” x 80” exterior doors for pricing)	204.40
	Single hung 3’ x 4’ windows	4134.00
09: Finishes	Gypsum wallboard	43.05
	Finished oak, ¾” x 2 ¼” select grade-red wood flooring 40%, nylon level loop with 3/8” nova pad 20 oz. carpet 40%, themes series 0.08 thick 2.9 performance appearance ratings in beige cameo vinyl flooring 15%, glazed floor tile ¼” thick better quality patterns 5%	7653.36
	#15 felt underlayment for roof	1857.10
	Job-built stairway	535.00
10: Specialties	2 full baths	10258.00
	1 half bath	3107.00
11: Equipment	40 gallon electric water heater	545.00
	Electrical	530.00
12: Furnishings	Kitchen sink	430.00
	Kitchen countertops with 14 L.F.	322.00
	Kitchen cabinets	474.00
	Lighting fixtures	3045.00
		Final Cost (including year differences, location factor, labor and markup) = **147,207.78**

(RSMeans, 2002), (Pray, 2009), (RSMeans, 2008), (RSMeans, 1996), (McArleton & Racusin, 2010) *(Please refer to Appendix F: Cost Estimation Analysis for more detailed calculations and features)*

(Note 1: Masonry is shown in Table 10 as $0.00.This is because the consultants gave a combined cost of the plaster and the installation of the bales and therefore that cost was applied to Thermal and Moisture Protection.

Note 2: It was kept in mind that the comparison between a standard post-and-beam house and the straw bale house would have variations due to the fact that certain aspects could either not be found after extensive research. However, a close alternative was induced in these circumstances)

The standard house totaled out to be $195,235.41, whereas the straw bale house summed up to be $147,207.78. This difference equates to having the straw bale structure be cheaper by $48,027.63. This difference can be attributed to the fact that straw bale construction entails the use of less expensive materials.

Initially, this price difference may seem like a straw bale home is considerably less expensive than a standard home. However, this straw bale house cost does not factor in the lifecycle cost of a straw bale structure. This includes the maintenance cost of a home in terms up keeping the quality of a plaster-finish. Several years of not maintaining a plaster can cause excessive weathering. With time, cracking becomes imminent, which increases the probability for straw to be exposed to excessive moisture. Repair costs could differ depending on the degree of damage (i.e. whether there is structural damage, if a whole wall needs to be replaced). Even though maintenance costs can also be reflected in standard homes, the main difference within cost of repairs in regards to a straw bale structures lies in the fact that fewer professionals are knowledgeable and or available for repairing damages within straw bale structures.

5. Conclusions and Recommendations

In this project, the correlation between various plaster components and compositions and straw bale performance was evaluated in terms of vapor permeability, thermal resistivity, and compression strength. These studies provide a base for rational application of a plastered-straw bale system within cold climate regions. Literature, laboratory, and exchanges with a consultant were used to design a two-story, wrap-around straw bale residential structure for Worcester, Massachusetts in the context of the load-carrying requirements presented in the *Commonwealth of Massachusetts State Building Code (780 CMR)*. A cost comparison between a tradition post-and-beam structure and a wrap-around straw bale post-and-beam structure was conducted in order to assess the cost effectiveness of straw bale construction. Using all of these findings, it was determined that straw bale construction can be utilized as a viable, alternate construction method within Massachusetts. The following sections summarize the deductions made from analyzing the founded data within this project.

Strength

In order to evaluate the performance of a plastered-straw bale wall system subjected to compressive, lateral and shear loads, dual-sided plastered bales were placed under such loading conditions in WPI's laboratory. During the test process, both plastered and unplastered bales exhibited elastic deformation under uniform loading and demonstrated significant capacity. When the dual-sided-plastered bale underwent a lateral loading, it showed that the plaster added significant strength to the overall loading capacity of the bale. Under the same deformation, the plastered bale was able to withstand over 6,000 LBF while the unplastered bale only withheld a little over 3,000 LBF.

The four configurations that were tested for the earthen-based plaster specimens included a lime-and-sand based plaster, a 10% manure-to-mix batch, a 25% manure-to-mix batch, a 40% manure-to-mix batch, and an earthen-control sample. From the available data, it can be suggested that the addition of manure to a mix does increase the compression strength of an earthen-based plaster as all the maximum loads of the high manure content specimens were higher than the average compression strength of the earthen-based plasters. Additionally, the data suggests that earthen-based plasters are stronger than lime-and-sand based plasters. However, it must be noted that the main function of lime-and-sand plasters is for the use as a final coating to prevent weathering, and not to produce high structural strength.

Vapor Permeability

As plaster is such a critical component of straw bale structures, seven different configurations of plasters were tested for their vapor permeability capacities. This included the fiber reinforced-lime-and-cement plaster, the earthen-control plaster, the 10%, 30%, and 50% lime-to-clay plasters, and the 10%, 25%, and 40% manure-to-mix plasters.

The two fiber reinforced-lime-and-cement plaster samples demonstrated negligible permeability because no water transmission was observed within the two samples whatsoever. Therefore, it was deduced that cement-based plasters with high cement content are highly impermeable.

The earthen-based specimens, on the other hand, did demonstrate some vapor permeability within testing. However, it must be noted that the apparatus used for this test was faulty. Nevertheless, even though limited and highly-variable data was acquired, some trends were formulated from the data that was acquired. In terms of the lime-to-clay-based samples, it can be presumed that a higher portion of lime increases the vapor permeability of a plaster.

Thermal Resistivity

Two entirely-plastered bales, encased in either the lime-and-cement-based plaster or the earthen-control plaster, along with six cylindrical plaster specimens, consisting of lime-and-sand, earthen-control, and lime-and-cement plasters, were tested for their thermal resistivity capacities. The specimens were probed with thermal couplings and were exposed to several temperature changes in WPI's environmental chamber for duration of 60 hours.

Generally speaking, the least amount of temperature change occurred within the earthen-plastered bales. This demonstrates that earthen-based plasters are more thermally resistant than lime-and-cement plasters when applied onto bales. The R-Value of the earthen- plastered bale was calculated to be 10.97 per inch whereas the lime-and-cement-plastered bale was calculated to have an R-value of 7.39 per inch.

This data also suggests that the plaster itself does not act as the main thermal insulator within a plastered-straw bale system. As the couplings were probed closer to the surface of the bale, the difference of temperature change between the thermal couplings and the ambient temperature was reduced.

Structural and Architectural Design

A one-family, two-story residential structure was both architecturally and structurally designed in compliance with the dimension and load-carrying requirements stated in *780 CMR* to evaluate the applicability of straw bale construction in Massachusetts. By strictly following the code requirements, floor plans and post-and-beam structural plans for the designed house were developed. Overall, designing the structural post-and-beam frame for the straw bale structure was simple as the floor layout incorporated a simple design and the process of following the structural design criteria and standards presented in *780 CMR* and *NDS* documents was straightforward.

Cost Effectiveness

In this project, the difference in cost between a standard post-and-beam structure and a wrap-around post-and-beam straw bale structure was analyzed in order to conclude how cost effective straw bale construction can be in Massachusetts. After reviewing the *RS Means* costs, and including a 3% addition for inflation and 20% for mark up for each structure, it was concluded that constructing a one-family, two-story residential structure in Worcester, MA with straw bale would provide a less expensive initial cost by approximately $48,027.63.

However, contrary to standard construction methods, the knowledge of maintenance costs or cost of repairs for straw bale structures is limited and can vary drastically depending on various degrees of weathering or moisture damage within a plastered-straw bale system. It is recommended that further analyses should be conducted in regards to the life-cycle and upkeep of straw bale structures in cold climate regions in order to determine the overall cost effectiveness of straw bale construction.

Limitations

Although the procedures of this project were carefully prepared and executed, it is important to note that there were several limitations to the end results of this project. The various restricting factors included faulty equipment, insufficient laboratory space, funding, and time, a lack of experience and knowledge on design and manual construction of straw bale components, and other miscellaneous factors that could have been overlooked.

For example, the research members were not straw bale construction experts, and therefore, the quality of the plastered specimens that experienced uniform loading could have been compromised due to the inexperience of the research members. Another constraint was time. The limited amount of time that was allowed to conduct this project constrained the amount of qualitative tests and analyses that could have been performed with the resources that were available. Moreover, the laboratory space where the tests took place was limited, which therefore constrained the utilization of how many resources could be used for testing. Finally, funding constraints were also prominent within this project. With a budget, the costs had to be spent wisely between supplies and consultations with experts.

Recommendations for Further Research

Overall, the test results, analyses and conclusions of this project state that different components within plaster mixes prove to possess their own relative merits. However, just because certain components of a mix show prominent merits in compression strength, vapor permeability, or thermal resistivity, it does not necessarily follow that that component should dominate the design of the entire mix. As stated in Section, 2.2.2, a plaster mix is effective when its components correlate together as a system.

In this project, even though cement-based plasters did have a significantly greater loading capacity than the earthen-based plasters, it should not instigate the withdrawal of earthen-based plasters from being utilized in straw bale construction because cement-based plasters are very impermeable, which is unfavorable for straw bale construction in cold climates. In addition, just because high lime-based plasters were the most permeable, and because the earthen-control plaster was most thermally resistant in this project, it is all the more difficult to deduce what kind of plaster composition would be ideal to utilize within straw bale construction in cold climate areas. Therefore, it is recommended that more testing should be evaluated in terms of various plaster configurations and compositions. It is recommended that multiple specimens should be created per each configuration, and that all of the configurations should undergo all of the spectrums of testing procedures.

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Appendix A: Calculations: Determining Quantities

Thermal Testing	Dimensions	No.	Total Volume of Mix Needed (in3)	Total to be made with ~20% waste
Bales				
Cement-plastered bale (5 sides)	[(42" x 19") + 2(16" x19") + 2(42" x 16")] * 1.5"	1	4125	4950
Earthened plastered bale (5 sides)	[(42" x 19") + 2(16" x19") + 2(42" x 16")] * 1.5"	1	4125	4950
Unplasted bale	NA	1	NA	
Cylinders				
Fiber Reinforced Lime-Based Cement Plaster	3" dia x 6"	2	84.82	101.784
Earthen Plaster (control)	3" dia x 6"	2	84.82	101.784
Lime Plaster	3" dia x 6"	2	84.82	101.784

Vapor Permability Testing

Cylinders

Fiber Reinforced Lime-Based Cement Plaster	4" dia x 4"	2	226.4	271.68
Earthen Plaster (control)	4" dia x 4"	2	226.4	271.68
Earthen w/ 10% lime-to-clay	4" dia x 4"	2	226.4	271.68
Earthen w/ 30% lime-to-clay	4" dia x 4"	2	226.4	271.68
Earthen w/ 50% lime-to-clay	4" dia x 4"	2	226.4	271.68
Earthen w/ 10% manure-to-mix	4" dia x 4"	2	226.4	271.68
Earthen w/ 25% manure-to-mix	4" dia x 4"	2	226.4	271.68
Earthen w/ 40% manure-to-mix	4" dia x 4"	2	226.4	271.68

Load Testing

Bales

Earthen-plastered bale (2 sides)	2(42" x 16") * 1.5"	4	8064	9676.8

Cylinders

Fiber Reinforced Lime-Based Cement Plaster	3" dia x 6"	2	84.82	101.784
Earthen Plaster (control)	3" dia x 6"	2	84.82	101.784
Lime Plaster	3" dia x 6"	2	84.82	101.784
Earthen w/ 10% manure-to-mix	3" dia x 6"	2	84.82	101.784
Earthen w/ 25% manure-to-mix	3" dia x 6"	2	84.82	101.784
Earthen w/ 40% manure-to-mix	3" dia x 6"	2	84.82	101.784

Total Quantities per Batch	Total to be made with ~10% waste (in3)		Total to be made with ~10% waste (ft3)
Fiber reinforced lime-based cement plaster	4973		2.88
Earthen plaster (control)	13844		8.01
Lime plaster	187		0.11
Earthen w/ 10% lime-to-clay	249		0.14
Earthen w/ 30% lime-to-clay	249		0.14
Earthen w/ 50% lime-to-clay	249		0.14
Earthen w/ 10% manure-to-mix	342		0.20
Earthen w/ 25% manure-to-mix	342		0.20
Earthen w/ 40% manure-to-mix	342		0.20

Appendix B: Determining Dry Ingredient Quantities

DRY ONLY								
Earthen Plaster (control)		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
	Part	3.00	0.50	8.00	0.50	1.00	TBD	13.00
	Part of Total	0.23	0.04	0.62	0.04	0.08		1.00
	Volume per part for 5 ft3	1.15	0.19	3.08	0.19	0.38	TBD	5.00
	Density of part (kg/ft3)	22.00	12.16	46.82	29.68	1.68		
	Mass per part (kg)	23.57	2.17	133.77	5.30	0.60	TBD	165.41

Lime Plaster		Lime	Sand	Water				Total (Dry)
L1, L2	Part	1.00	3.00	TBD				4.00
	Part of Total	0.25	0.75					1.00
	Volume per part for .11 ft3	0.028	0.083	TBD				0.11
	density (kg/ft3)	12.17	46.82					
	Mass (kg)	0.33	3.86	TBD				4.20

Earthen w/ 10% lime-to-clay		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 1A, 1B	Part	0.90	0.10	2.50	0.50	1.00	TBD	5.00
	Part of Total	0.18	0.02	0.50	0.10	0.20		1.00
	Volume per part for .14 ft3	0.025	0.003	0.070	0.014	0.028	TBD	0.14
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68		
	Mass (kg)	0.55	0.03	3.28	0.42	0.05	TBD	4.33

Earthen w/ 30% lime-to-clay		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 2A, 2B	Part	0.70	0.30	2.50	0.50	1.00	TBD	5.00
	Part of Total	0.14	0.06	0.50	0.10	0.20		1.00
	Volume per part for .14 ft3	0.020	0.008	0.070	0.014	0.028	TBD	0.14
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68		

	Mass (kg)	0.43	0.10	3.28	0.42	0.05	TBD	4.27

Earthen w/ 50% lime-to-clay		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 3A, 3B	Part	0.50	0.50	2.50	0.50	1.00	TBD	5.00
	Part of Total	0.10	0.10	0.50	0.10	0.20		1.00
	Volume per part for .14 ft3	0.014	0.014	0.070	0.014	0.028	TBD	0.14
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68		
	Mass (kg)	0.31	0.17	3.28	0.42	0.05	TBD	4.22

Earthen w/ 10% manure-to-mix		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 4A, 4B, 4C, 4D	Part	0.86	0.14	2.50	0.45	1.00	TBD	4.95
	Part of Total	0.17	0.03	0.51	0.09	0.20		1.00
	Volume per part for .20 ft3	0.035	0.006	0.101	0.018	0.040	TBD	0.20
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68		
	Mass (kg)	0.76	0.07	4.73	0.54	0.07	TBD	6.17

Earthen w/ 25% manure-to-mix		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 5A, 5B, 5C, 5D	Part	0.86	0.14	2.50	1.13	1.00	TBD	5.63
	Part of Total	0.15	0.02	0.44	0.20	0.18		1.00
	Volume per part for .20 ft3	0.031	0.005	0.089	0.040	0.036	TBD	0.20
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68		
	Mass (kg)	0.67	0.06	4.16	1.19	0.06	TBD	6.14

Earthen w/ 40% manure-to-mix		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 6A, 6B, 6C, 6D	Part	0.86	0.14	2.50	1.80	1.00	TBD	6.30
	Part of Total	0.14	0.02	0.40	0.29	0.16		1.00
	Volume per part for .20 ft3	0.027	0.004	0.079	0.057	0.032	TBD	0.20
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68		
	Mass (kg)	0.60	0.05	3.72	1.70	0.05	TBD	6.12

Appendix C: Determining Water Ratios

WITH WATER								
Earthen Plaster (control)		Clay	Lime	Sand	Manure	Straw	Water	Total
1ST BATCH	Part	3	0.5	8	0.5	1	3.04	16.04
	Part of Total	0.19	0.03	0.50	0.03	0.06	0.19	1
	Volume per part for 6.17 ft3	1.15	0.19	3.08	0.19	0.38	1.17	6.17
	Density of part (kg/ft3)	22	12.16	46.82	29.68	1.68	28.3	
	Mass per part (kg)	23.6	2.2	133.8	5.3	0.6	33.1	198.5

Lime Plaster		Lime	Sand	Water				Total
L1, L2, L3, L4	Part	1.00	3.00	1.82				5.82
	Part of Total	0.19	0.50	0.31				1.00
	Volume per part for .16 ft3	0.03	0.08	0.05				0.160
	density (kg/ft3)	12.17	46.82	28.30				
	Mass (kg)	0.37	3.75	1.42				5.53

Earthen w/ 10% lime-to-clay		Clay	Lime	Sand	Manure	Straw	Water	Total
Specimens: 1A, 1B	Part	0.90	0.10	2.50	0.50	1.00	1.82	6.79
	Part of Total	0.13	0.02	0.37	0.07	0.15	0.27	1
	Volume per part for .19 ft3	0.025	0.003	0.070	0.014	0.028	0.051	0.191
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68	28.30	
	Mass (kg)	0.55	0.04	3.28	0.42	0.05	1.44	5.77

Earthen w/ 30% lime-to-clay		Clay	Lime	Sand	Manure	Straw	Water	Total (Dry)
Specimens: 2A, 2B	Part	0.7	0.3	2.5	0.5	1	1.82	6.79
	Part of Total	0.11	0.04	0.37	0.07	0.15	0.27	1
	Volume per part for .19 ft3	0.020	0.008	0.070	0.014	0.028	0.051	0.191
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68	28.30	
	Mass (kg)	0.44	0.10	3.28	0.42	0.05	1.44	5.72
Earthen w/ 50% lime-to-		Clay	Lime	Sand	Manure	Straw	Water	Total

clay								
Specimens: 3A, 3B	Part	0.5	0.5	2.5	0.5	1	1.68	6.68
	Part of Total	0.07	0.07	0.37	0.07	0.15	0.25	1
	Volume per part for .19 ft3	0.014	0.014	0.07	0.014	0.028	0.047	0.187
	density (kg/ft3)	22	12.16	46.82	29.68	1.68	28.3	
	Mass (kg)	0.31	0.17	3.28	0.42	0.05	1.33	5.55

Earthen w/ 10% manure-to-mix		Clay	Lime	Sand	Manure	Straw	Water	Total
Specimens: 4A, 4B, 4C, 4D	Part	0.86	0.14	2.5	0.45	1	2.72	7.67
	Part of Total	0.11	0.02	0.33	0.06	0.13	0.35	1.00
	Volume per part for .31 ft3	0.035	0.006	0.101	0.018	0.040	0.110	0.310
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68	28.30	
	Mass (kg)	0.77	0.07	4.73	0.53	0.07	3.11	9.29

Earthen w/ 25% manure-to-mix		Clay	Lime	Sand	Manure	Straw	Water	Total
Specimens: 5A, 5B, 5C, 5D	Part	0.86	0.14	2.50	1.13	1.00	1.54	7.17
	Part of Total	0.12	0.02	0.35	0.16	0.14	0.21	1
	Volume per part for .26 ft3	0.031	0.005	0.089	0.040	0.036	0.055	0.256
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68	28.30	
	Mass (kg)	0.68	0.06	4.17	1.19	0.06	1.56	7.71

Earthen w/ 40% manure-to-mix		Clay	Lime	Sand	Manure	Straw	Water	Total
Specimens: 6A, 6B, 6C, 6D	Part	0.86	0.14	2.50	1.80	1.00	1.39	7.69
	Part of Total	0.11	0.02	0.33	0.23	0.13	0.18	1
	Volume per part for .24 ft3	0.027	0.004	0.079	0.057	0.032	0.044	0.243
	density (kg/ft3)	22.00	12.16	46.82	29.68	1.68	28.30	
	Mass (kg)	0.59	0.05	3.70	1.69	0.05	1.25	7.33

Part →	Clay	Lime	Sand	Manure	Straw	Water	Total
Batch ↓							
Earthen Plaster (control) - 1st Batch	3.00	0.50	8.00	0.50	1.00	3.04	16.04
Lime Plaster		1.00	3.00			1.82	5.82
Earthen w/ 10% lime-to-clay	0.90	0.10	2.50	0.50	1.00	1.82	6.79
Earthen w/ 30% lime-to-clay	0.70	0.30	2.50	0.50	1.00	1.82	6.79
Earthen w/ 50% lime-to-clay	0.50	0.50	2.50	0.50	1.00	1.68	6.68
Earthen w/ 10% manure-to-mix	0.86	0.14	2.50	0.45	1.00	2.72	7.67
Earthen w/ 25% manure-to-mix	0.86	0.14	2.50	1.13	1.00	1.54	7.17
Earthen w/ 40% manure-to-mix	0.86	0.14	2.50	1.80	1.00	1.39	7.69

Appendix D: Notes from Conference Call with Ace McArleton (11/30/10)

Interior Walls: The interior walls should be the standard 16" o.c. framed walls with regular lumber and finished with drywall. The walls should be 6" thick using 2x4.

Plumbing: The plumbing in a straw bale home will be the same as a normal house because the plumbing runs through interior walls.

Electrical: The electrical wiring runs through the bales using regular electrical boxes. This is completed in which the wires romex? through by carving channels through the bales and chase the wires through.

Framing: There are two exterior frames for a straw bale house. There is one that can be referred to as the "interior frame" in which it is built to hold and support the entire structure including the roof whereas there is an "exterior frame" which is constructed so that the windows and doors can be supported.

Roofing: Any roof truss can be attached to a straw bale structure.

Costs: The cost to build a straw bale structure is determined by the surface area of the walls. For Ace's company, the rate to install the bale base and apply the finish coat for a stick frame building not including the stick frame itself is $12-13/ sqft.

Foundation: Any foundation can be used as long as it keeps the bales 18-24" from the finish grade. One type of foundation that can be used is the Alaskan slab (also known as slab on grade) in which it is insulated beneath frost line. The straw bales cannot sit on top of the concrete foundation because it will pick up too much moisture, thus there is a small wall that is commonly built knee level high with plywood for the straw bales to sit on. There are capillary breaks that are created between the cement foundation and the small plywood wall which are filled with cellulose. It is very important that the foundation avoids heaving from the frost line. Roofing felt or tar paper can be placed between the cement wall and the little stud wall and the bales. If the foundation is not high enough, a toe up (which is a small wall) needs to be added.

Recommendations: When designing the straw bale house, the design should always have a passive solar energy concept kept in mind. Thus, the main entrance should be on the north side of the house and there should be more windows on the south side of the house. The bedrooms should be on the east side of the house so that you wake up when the sun rises.

Software: Usually a straw bale project consists of creating a program. This program generally consists of a detailed description of what the project is trying to achieve, affordability, etc.

Maintenance: In order to maintain a straw bale structure, it is important to paint a thin wash every 5-10 years.

There are three general rules to follow when building a straw bale structure:

(1) The foundation should be lifted up so that snow does not pile against them.

(2) The roof needs to have a large enough overhang.

(3) The plaster should be earth plaster topped with lime plaster.

Appendix E: Structural Analysis of a One-Family, Two-Story Straw Bale Structure in Worcester, MA

MQP Design of One-family Two-Story Wood Framed House 1/

Uniformly Distributed Live Load: $\boxed{L_r = 20 \text{ psf}. \quad L_o = 40 \text{ psf}}$

Basic Wind Speed: 90 MPH

Ground Snow Load: $p_g = 40$ psf

Design Snow Load (Mass Building Code)

$$S = C_s 0.7 C_e C_t I p_g$$

$$= (1.0)(0.7)(1.1)(1.0)(1.0)(40)$$

$$= \boxed{30.8 \text{ psf} = S}$$

$C_s = 1.0$ (roof slope less than 30 deg)

$C_e = 1.1$ (sheltered roof)

$C_t = 1.0$ (high thermal resistance)

$I = 1.0$ (Occupation Cate. II)

(ASCE Chapter 7)

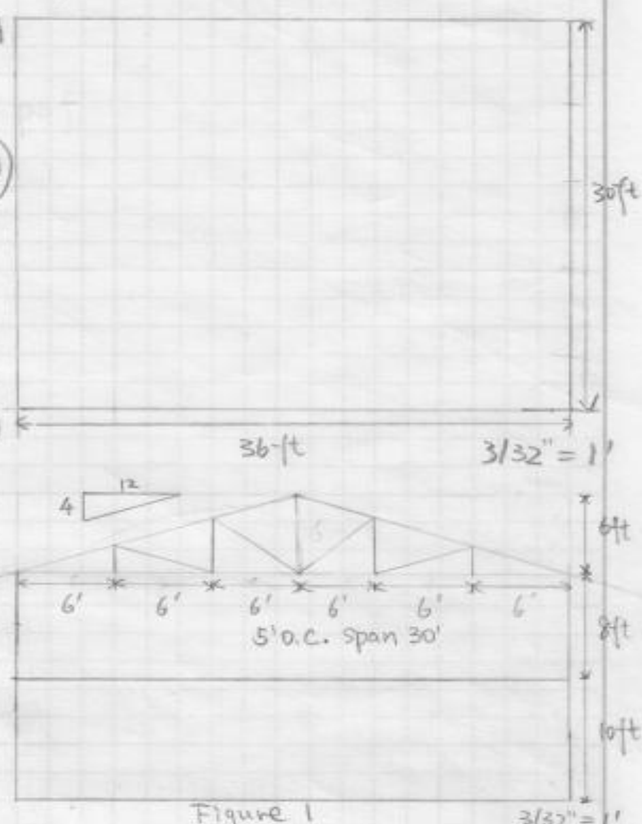

Figure 1

Design Wind Forces:

$V = 90$ MPH $I = 1.0$ (Importance Factor)

$h_{mean} = \frac{18+24}{2} = 21 \text{ ft} \Rightarrow \lambda = 1.29$

$\theta = \tan^{-1}(6/18) = 18.43°$

Horizontal Wind Pressure on Verticle Projection of Building:

Wall Forces: Zone A for $\theta = 18.43°$ $P_{s30} = 17.8$ psf

(ASCE Figure 7-2) Zone C $P_{s30} = 11.9$ psf

Zone B $P_{s30} = -4.7$ psf

Zone D $P_{s30} = -2.6$ psf

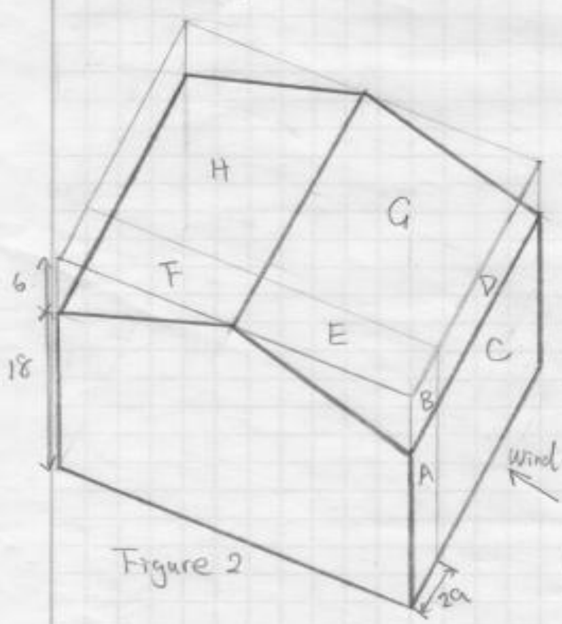

Figure 2

2/

Design Wind Pressure: $P_s = \lambda K_{zt} I P_{s30} = 1.29(1.0)(1.0)P_{s30} = 1.29 P_{s30}$

$\therefore P_{SA} = 1.29(17.8) = 22.96$ psf (inward pressure) $P_{SB} = 1.29(-4.7) = -6.06$ psf (outward pressure)

$P_{SC} = 1.29(11.9) = 15.35$ psf $P_{SD} = 1.29(-2.6) = -3.35$ psf

Verticle Wind Pressure on Horizontal Projection of Building

Zone E: $P_{s30} = -15.4$ psf Zone F: $P_{s30} = -10.7$ psf Zone G: $P_{s30} = -10.7$ psf

Zone A: $P_{s30} = -8.1$ psf

Design Wind Pressure: $P_{SE} = 1.29(-15.4) = -19.87$ psf $P_{SF} = 1.29(-10.7) = -13.8$ psf

(upward pressure) $P_{SG} = 1.29(-10.7) = -13.8$ psf $P_{SH} = 1.29(-8.1) = -10.45$ psf

Higher End Zone Distance: $0.4 h_{mean} = 0.4(21\text{ ft}) = 8.4$ ft

0.1 (least width of Structure) = 0.1(30) = 3 ft

a = lesser of ($0.4 h_{mean}$ or $0.1b$) = 3 ft

$2a = 2(3) = 6$ ft

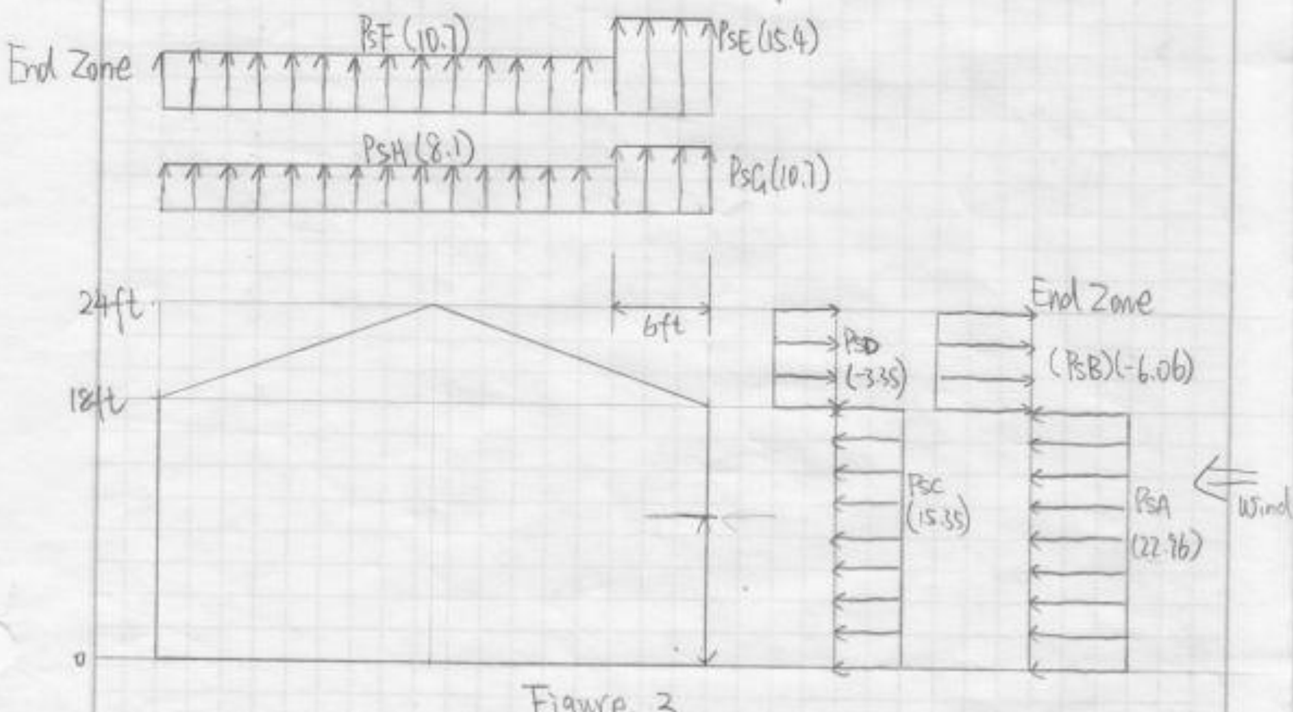

Figure 3

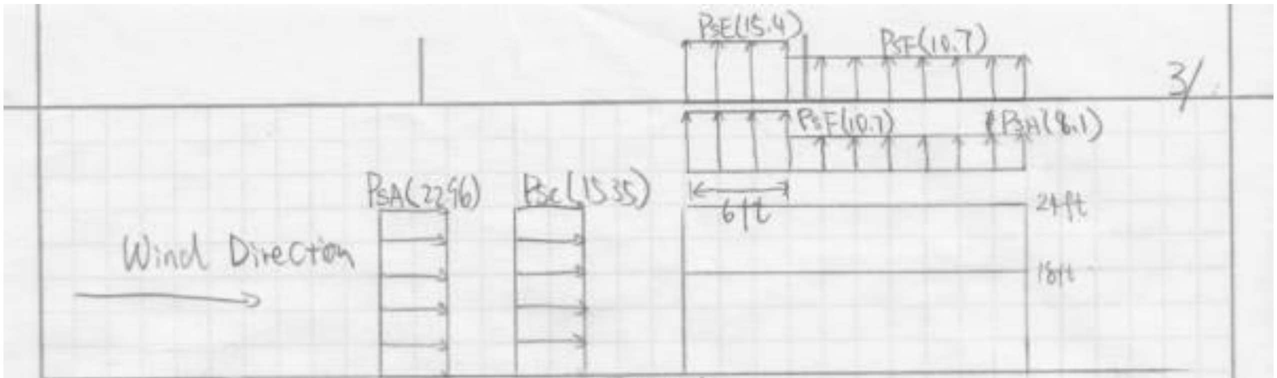

Figure 4

Roof Truss:
(2x4 Douglas Fir Select Structure)
15 @ 24" O.C.

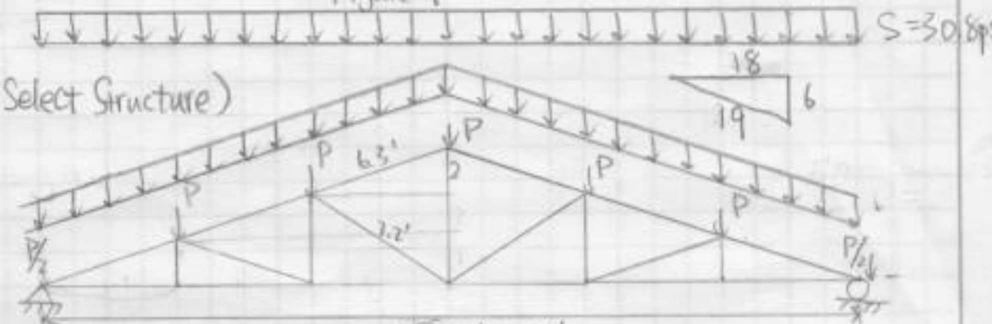

Figure 5

(13.67)

Snow load = 30.8 psf   Roof live load L_r = 20 psf

Roof Dead load: Insulation = 1.5 psf   Suspended ceiling (acoustic tile) = 1.0 psf
("Design of Wood Structures 6th Edition")   Roofing (5-ply with gravel) = 6.5 psf   Reroofing = 2.5 psf

Truss (2x4 24" O.C) Total Weight:

$$\text{Total length} = (6' \times 7) + (6.3' \times 8) + (7.2' \times 2) + (2' \times 2) + (4' \times 2) = 118.8\ ft$$

$$\text{Total Volume} = (5.25\ in^2)(118.8\ ft \times 12) = 7484.4\ in^3 = 4.33\ cf \quad (\text{NDS T1A})$$

$$\text{Density} = 62.4\left[\frac{G}{1+G(0.009)(m.c)}\right]\left[1+\frac{m.c.}{100}\right] \quad G = 0.5\ (\text{NDS T8A})$$

$$= 62.4\left[\frac{0.5}{1+(0.5)(0.009)(19)}\right]\left[1+0.19\right] = 34.2\ lb/ft^3$$

$$\text{Weight} = (34.2)(4.33) = 148.19\ lb \quad \text{Total Weight} = (148.19)(15) = 2221.9$$

$$\text{Dead Load} = (2221.9)/(36' \times 30') = 2.06\ psf$$

$$\text{Total Roof Dead Load} = \left[2.06\left(\tfrac{19}{18}\right)\right] + 1.5 + 1.0 + 6.5 + 2.5 = 13.67\ psf$$

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Building Structure Design:

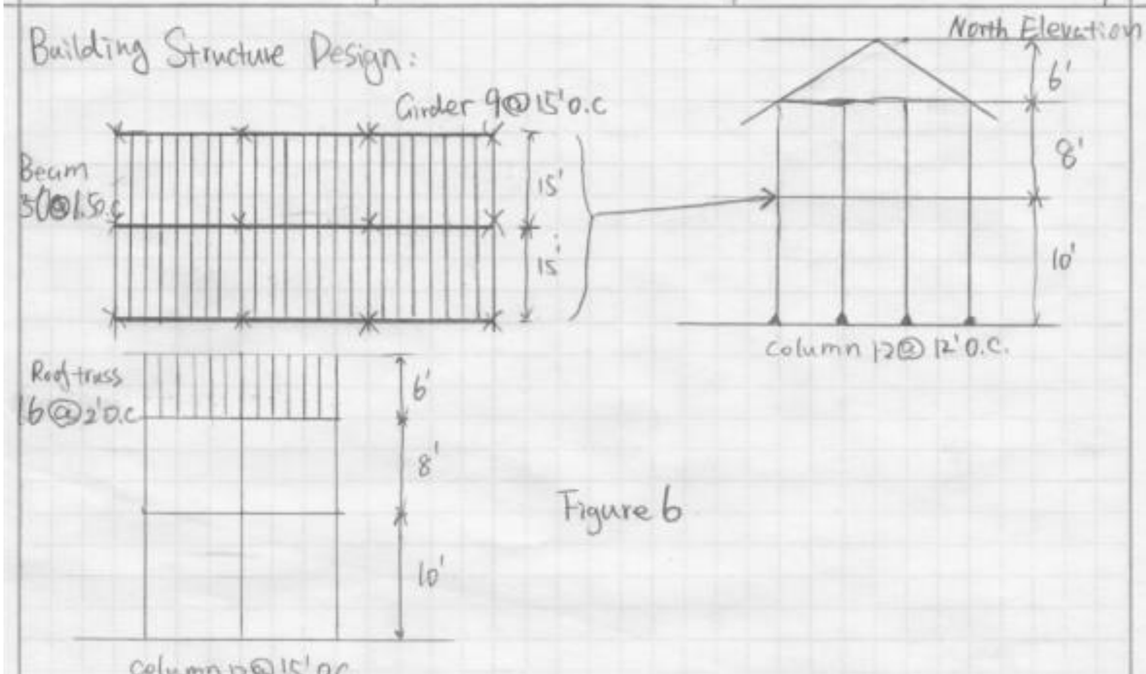
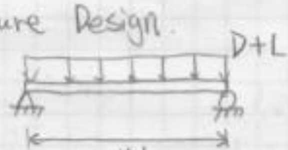


Figure 6

- Second Floor Structure Design

  - Beam 14@6' o.c



Tributary area for end beams : $A_1 = (15')(3') = 45$ sf

for interior beams : $A_2 = 2A_1 = 90$ sf

Floor dead load : Floor covering (lightweight concrete $1\frac{1}{2}$ in at 100 lb/ft^3) = 12.5

(Information From "Design of Wood Structures 6th Edition")

$1\frac{1}{8}$-in plywood (3 psf × $1\frac{1}{8}$ in) = 3.4

ceiling supports (2x4 at 24 in o.c) = 0.6

ceiling (1/2 in drywall, 5 psf × 1/2 in) = 2.5

= 19 psf

Partition wall Load = 25 psf

Total Dead load = 19 + 25 = 44 psf

Live load $L_o = 40$ psf $K_{LL} = 2$ (ASCE T4-2) $K_{LL}A_{T1}$(Edge Beam) = 2(15')(1.5) = 45 ft < 400

$K_{LL}A_{T2}$(Interior Beam) = 2(15)(3) = 90 sf < 400 ft

∴ $L = L_o = 40$ psf

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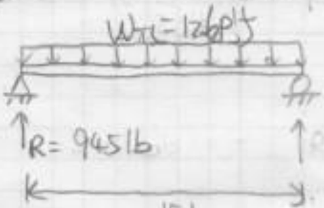
Use ASD : $C_D D = 0.9D = 0.9(44\ psf) = 39.6\ psf$

$C_D(D+L_r) = 1.0(D+L_r) = 1.0(44+40) = 84\ psf \leftarrow$ critical

$w_{TL} = (84)(15') = 120\ plf$



$V = 945\ lb$

$M = \frac{1}{8}wL^2 = 42525\ lb\cdot in$

Trial: choose Glulam Lumber Douglas Fur Select Structure (NDS T4A)

$F_b' = F_{bx}' = F_{bx}(C_D)(C_M)(C_t)(C_r)(C_F)(C_i)$

$= (1500)(1)(1.0)(1)(1)(1.15)(1.2)(1)$ assume $C_F = 1.2$

$= 2070\ psi$

Required $S = M/F_b' = 42525/2070 = 20.54\ in^3$

Try 3X8 $S_{xx} = 21.9\ in^3 > 20.54\ in^3$

Since the trail size is determined using $C_F = 1.2$

NDS Table 4A gives $C_F = 1.3 > 1.2$ OK

$f_b = M/S_{xx} = 42525/21.9 = 1941\ psi < F_b'$ OK

Check shear: $f_v = 1.5V/A = 1.5(945)/18.13 = 78.19\ psi$

$F_v' = F_v(C_D)(C_m)(C_t)(C_i) = 95(1)(1)(1.1)(1) = 104.5$

$> f_v$ OK

Deflection : $E' = E(C_M)(C_t)(C_i) = 1900{,}000(1)(1.1)(1) = 2090000\ psi$

$\Delta L = \frac{5W_L L^4}{384EI} = \frac{5(40)(15^4)(12^4)}{384(2.09\times10^6)(128.5)} = 0.49$

Allow $\Delta L = \frac{L}{240} = \frac{15\times12}{240} = 0.75 > 0.56$ OK

$\therefore$ $\boxed{\text{Use 3X8 Select Structure Douglas Fir MC} \leq 19 \text{ percent}}$

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Beam weight : 3x8 Area = 18.13 in² Volume X 50 pieces

$= (18.13in^2)(15 \times 12in)(50)$

$= 94.43 cf$

Density of wood $= 62.4 \left[\frac{G}{1+G(0.009)(m.c)}\right]\left[1+\frac{m.c}{100}\right]$ G= 0.5 (NDS T8A)

$= 62.4 \left[\frac{0.5}{1+(0.5)(0.009)(19)}\right]\left[1+0.19\right] = 34.2\ lb/ft^3$

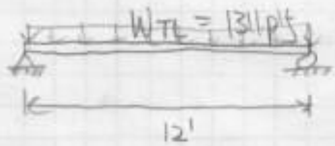
Weight of wood $= (94.43)(34.2) = 3229.4\ lb$

dead load of wood $= 3229.4 lb / (36' \times 30') = 3.45\ psf$

— Girder 9 @ 15' O.C. $C_D D = 0.9D = (0.9)(44+3.45) = 42.71\ psf$

$C_D(D+L) = (1)(47.45+40) = 87.45\ psf$

$w_{TL} = (87.45)(15) = 1311.75\ plf$



$V = 7870.5\ lb$ $M = 23598\ lb \cdot ft = 2.8 \times 10^5\ lb \cdot in$

Trial : choose Glulam Lumber Douglas Fir (NDS T4D)

$F_b' = F_{bx} = F_{bx}(C_D)(C_M)(C_t)(C_F)(C_i)$

$= (1500)(1)(1)(1)(1.2)(1)$

$= 1800\ psi$

Required $S = M/F_b' = 2.8 \times 10^5\ lb \cdot in / 1800\ psi = 157.32 in^3$

Try 8X12 $S_{xx} = 165.3 in^3$

$f_b = M/S_{xx} = 2.8 \times 10^5 lb\ in / 165.3 = 1693 psi < F_b'$ OK

Check shear $f_v = 1.5V/A = 1.5(7870)/150 = 78.7 psi$

$F_v' = F_v(C_D)(C_M)(C_t)(C_i) = 95\ psi > f_v$ OK

Deflection : $E' = E(C_M)(C_t)(C_i) = 1.6 \times 10^6 (1)(1)(1) = 1.6 \times 10^6 psi$

$\Delta L = \frac{5 w_L L^4}{384 EI} = \frac{5(40)(12 \times 12)^5}{384(1.6 \times 10^6)(950)} = 0.42$

Allow $\Delta L = L/240 = 12 \times 12/240 = 0.6 > 0.42$ OK

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∴ $\boxed{\text{Use } 8 \times 12 \text{ Douglas Fir Select Structure } MC \le 19 \text{ percent}}$

Girder weight : Density $= 34.2\ lb/ft^3$

Volume $= (86.25 in^2)(12 \times 12)(9)$

$= 64.69\ cf$

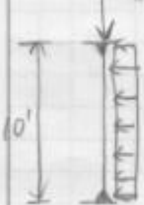
Weight $= (64.69)(34.2) = 3847.5\ lb$

dead load $= 3847.5\ lb / (36' \times 30') = 3.56\ psf$

Total Floor Dead Load $= 44 + 3.56 + 3.45 = 51 psf$

Column Design. see Figure 6, the critical bracing length is 10 ft.

Axial load = Floor Dead load (51 psf) + Floor Live load (40 psf)



lateral Force

+ Roof Dead load (13.67 psf) + Roof Snow load (30.8)

$= D + 0.75L + 0.75S = (51 + 13.67) + 0.75(40) + 0.75(30.8)$

$= 117.77\ psf\ (C_D = 1.25)$

(The weight of the column should also be considered)

Lateral Force (wind load) = 22.96 psf (critical)

Select Structure : Douglas Fir

Trial Size : $8\frac{3}{4}" \times 9"$ (NDS T. 1C)

Area : $78.75 in^2$

S_x : $118.1 in^3$

F_c : 1150 psi

F_b : 1500 psi

E_{min} : 1.6×10^6 psi

$f_c \rightarrow C_F = 1.0$

$f_b \rightarrow C_F = 0.86 F_b$

Dead Load of Column $= (34.2\ lb/ft^3)(78.75 in^2 \times 8 \times 12 / 12^3) / 78.75 in^2$

$= 1.9\ psf$

Total Axial Load $= 117.77 + 1.9\ psf = \boxed{119.67\ psf}$

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Axial

$P = (12' \times 15')(119.67\,psf) = 21540.6\,lb$

$f_c = \frac{P}{A} = \frac{21540.6\,lb}{78.75\,in^2} = 273.53\,psi$

$\left(\frac{l_e}{d}\right)_y = 0$

$\left(\frac{l_e}{d}\right)_x = \frac{10\,ft\,(12\,\frac{in}{ft})}{8.75\,in} = 13.72$

$E'_{min} = E_{min}(C_M)(C_t) = (1.6\times10^6)(1.0)(1.0) = \underline{1.6\times10^6\,psi}$

$c = 0.9$

$F_{cE} = \frac{0.822E'_{min}}{[(l_e/d)_{max}]^2} = \frac{0.822(1.6\times10^6)}{(13.72)^2} = 6986.88\,psi$

$F'_c = F_c(C_D)(C_M)(C_t)(C_F)(C_i)$

$F'_c = 1150(1.25)(1.0)(1.0)(1.0)(1.0)$

$\underline{F'_c = 1437.5\,psi}$

$\frac{F_{cE}}{F'_c} = \frac{6986.88}{1437.5} = 4.86$

$\frac{1+F_{cE}/F'_c}{2c} = \frac{1+4.86}{2(0.9)} = 3.25$

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$$C_P = \frac{1 + F_{cE}/F_c'}{2c} - \sqrt{\left(\frac{1 + F_{cE}/F_c'}{2c}\right)^2 - \frac{F_{cE}/F_c'}{c}}$$

$$C_P = 3.25 - \sqrt{(3.25)^2 - \frac{4.86}{0.9}}$$

$C_P = 0.98$

$F_c' = F_c(C_D)(C_M)(C_t)(C_F)(C_P)(C_i)$

$F_c' = (1150)(1.25)(1.0)(1.0)(1.0)(0.98)(1.0)$

$F_c' = 1408.75\ psi > f_c = 273.53\ psi$ OK

Bending:

$\omega = 22.96\ psf\,(10ft) = 229.6\ \frac{lb}{ft}$

$229.6\ \frac{lb}{ft} \times \frac{1ft}{12in} = 19.13\ \frac{lb}{in} = \omega$

$L = 10ft \times \frac{12in}{1ft} = 120in$

$$M = \frac{\omega L^2}{8} = \frac{(19.13\frac{lb}{in})(120in)^2}{8} = 34434\ in\cdot lb$$

$$f_b = \frac{M}{S} = \frac{34434\ in\cdot lb}{118.1} = 291.75\ psi$$

$F_b' = F_b(C_D)(C_M)(C_t)(C_L)(C_F)(C_r)(C_i)$

$F_b' = 1500(1.25)(1.0)(1.0)(1.0)(0.98)(1.0)(1.0)$

$F_b' = 1837.5\ psi > f_b = 291.5\ psi$ OK

10/

$F_{cE_x} = F_{cE} = 6986.88$ psi

$$\left(\frac{f_c}{F'_c}\right)^2 + \left(\frac{1}{1 - f_c/F_{cE_x}}\right)\frac{f_{bx}}{F'_{bx}} = \left(\frac{273.53}{1408.75}\right)^2 + \left(\frac{1}{1 - \frac{273.53}{6986.88}}\right)\frac{291.5}{1837.5}$$

$0.2 < 1.0$ ok

Therefore, column size chooses 8 ¾" × 9" Douglas Fir Select Structure

Appendix F: Cost Estimation Analysis

[illegible]	Natural [illegible]		1/14

An average two story post and beam house was calculated in order to find an estimate price for the house. The RS Means Square Foot Costs (200[illegible]) book used in order to find the estimate. The estimate used the same square feet as the house that was designed (See Figure __) and closely followed the aspects of the designed house in which the following calculations were made:

Length x Width = Living Area

36' + 2' (overhang) + 2' (overhang) = 40'

30' x 40' = 1200 ft² Living Area

Exterior Wall (8" Log - [illegible]) : (p.[illegible] of RS Means Square Foot Costs)

For 1200 ft² → Exterior Wall $[illegible]/ft²

1200 ft² ($101.[illegible] / ft²) = $122[illegible]

Half Bath: +$3,0[illegible]

Full Bath: +$5[illegible]

Total Cost = $(122[illegible] + 3[illegible] + 5[illegible])

Total Cost = $130346.00

2/14

Because the RS Means Square Foot Costs is a 2008 version, 3% must be added to the total cost for each year since 2008 (therefore 6% must be added).

\$130396.00(0.06) = \$7823.76

\$(130396 + 7823.76) = \$138,219.76

The location of the house is important to the total cost and therefore a Location Factor must be taken into consideration:

Location Factor for Worcester, MA = 1.13

\$138,219.76(1.13) = \$156,188.33

A markup must be taken into consideration and thus to achieve a markup of 20%, 25% must be added into the cost (National Construction Estimator p.5).

\$156,188.33(0.25) = \$39047.08

\$156,188.33 + \$39047.08 = $\boxed{\$195,235.41}$

Cost Estimation | Straw Bale House | 3/14

A cost estimation was conducted for the straw bale house which has been designed (see Figure ___). The following calculations demonstrate how this cost estimation was completed. The fixtures in the house follow the average post + beam house and the fixtures in an average house according to RS Means Square Foot Costs 2008 p. 27

Length × Width = Living Area

36' + 2' (overhang) + 2' (overhang) = 40'

30' × 40' = 1200 ft² = Living Area

Excavation:

(RS Means Site Work + Landscape Cost Data/2003) p.411)

Excavation + Fill for 1000 ft², 4' sand, gravel or common earth, on site storage = \$0.68/ft²

$\frac{\$0.68}{1000} = \frac{1200}{x}$

$1000x = 816$

$x = \$0.82/ft^2$

$1200\ ft^2 \left(\frac{\$0.82}{ft^2}\right) = \$984.00$

Foundation

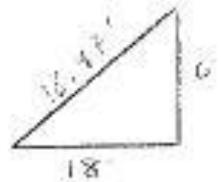
(RS Means: Site Work + Landscape Cost Data 2003 p. 410)

Slab on grade, 4" thick, non industrial, non reinforced = \$3.21/ft²

$1200\ ft^2 \left(\frac{\$3.21}{ft^2}\right) = \$3852.00$

4/14

Roof Truss:



15 Roof Trusses, span = 36'

$A = \frac{1}{2}bh = \frac{1}{2}(18)(6) = 54\ ft^2$

$A = 2 \times 54\ ft^2 = 106\ ft^2$ for whole truss

(National Construction Estimator 2009 p.405)

2"x4" Fink Truss "W" w/ 24" o.c. = \$2.76/ft²

$108\ ft^2\ (\$2.76/ft^2) = \$298.00$

$15 \times \$298 = \$4471.20$

Beams:

(Building Construction Data 2009 RS Means p.161)

3"x8" → amount = 50
span = 15'

$50 \times 15' = 750' < 1000'$ ok

Thousand Board Feet = \$2050.00

Columns:

(Building Construction Data 2009 RS Means p.162)

The 8 3/4" x 9" column could not be found in the cost estimator books and therefore the closest column to that size was used for the cost estimate (6"x10").

8 3/4" x 9" → amount = 12
height = 18'

$12' \times 18' = 216' < 1000'$ ok

5/14

alternative column:

6"x10" = $3,725 for 1,000 Board Feet

Girders:
(RS Means Building Construction Data 2009 p.161)

The 8"x12" Girder could not be found in the cost estimator books and therefore the next closest girder size (2"x12") was used for the estimate.

8"x12" → amount = 9
span = 12'

9 x 12' = 108' < 1000' ok

alternative girder:

2"x12" = $1,100 for 1000 Board Feet

"Exterior Frame":

(National Construction Estimator 2009 p. 398)

2"x4" → amount = 13 columns x 4 sides = 56
height = 24' (at most)

56 x 24' = 1,344' > 1,000 Board Feet

Therefore 2 units are need

2"x4" = $548.00 (for one unit)

2 units x $548.00 = $1096.00

6/14

Exterior Walls:

Deva's and Ace's company charge
\$14-20/Sq. ft of wall space for installing
and plastering the straw walls.

height × length = Sq. ft of wall space
$18' \times 30' = 540\ ft^2$

This wall space is on 2 sides of the house
so...

$2 \times 540\ ft^2 = \underline{1080\ ft^2}$

height × width = Sq. ft of wall space
$24' \times 36' = 864\ ft^2$

this wall space is on 2 sides...,
$2 \times 864\ ft^2 = \underline{1,728\ ft^2}$

$(1080 + 1728)\ ft^2 = \underline{2808\ ft^2}$ of total wall space

average price $= \frac{14+20}{2} = \underline{\$17/\text{Sq ft}}$

$2808\ ft^2 \left(\frac{\$17}{ft^2}\right) = \underline{\$47736}$ for total wall space

7/14

Roofing:

(RS Means Repair + Remodeling Cost Data 1997 p.137)

#15 felt underlayment = \$8.20/100 sq.ft.

$18.97' + 2'(\text{overhang}) = 20.97'$

$2 \times 20.97' = 41.94'$

$15(\text{trusses}) \times 41.94' = 629.10'$

$36' \times 629.10' = 22647.60\ \text{ft}^2$

$22647.60\ \text{ft}^2 \times \left(\frac{\$8.20}{100\ \text{ft}^2}\right) = \underline{\$1857.10}$

Gutters and Downspouts:

(National Construction Estimator 2009 p.163)

Aluminum rain gutter, 5" box type, primed	
Gutter, 5", 10' lengths	= \$3.46/L.F
Inside or outside corner	= \$11.54 Ea.
Fascia support brackets	= \$2.02 Ea.
Gutter hanger and support	= \$1.58 Ea.
Section joint kit	= \$4.30 Ea.

$30'\left(\frac{\$3.46}{1\ \text{L.F.}}\right) = \underline{\$103.80}$

$36'\left(\frac{\$3.46}{1\ \text{L.F.}}\right) = \underline{\$124.56}$

$4(11.54 + 2.02 + 1.58 + 4.30) = \underline{\$77.76}$

$\$(103.80 + 124.56 + 77.76) = \underline{\underline{\$306.12}}$

4/14

120 yd^2 $\left(\frac{\$19.66}{yd^2}\right)$ = \$2359.20

40% of the floor in the house is carpet ...

0.40(2359.2) = \$943.68

Vinyl Flooring: Armstrong. Includes 10% waste and adhesive. (p.440)

Themes series, .08 thick, 2.9 Performance Appearance Rating:

Beige Cameo = \$25.30/sq yd.

120 yd^2 $\left(\frac{\$25.30}{yd^2}\right)$ = \$3036.00

15% of the flooring in the house is vinyl ..

0.15(3036.00) = \$455.40

Ceramic Tiles: (p.436)

Glazed Floor Tile, 1/4" thick

Better quality, patterns = \$11.66/sq. Ft

1080 ft^2 $\left(\frac{\$11.66}{ft^2}\right)$ = \$12592.80

5% of the flooring in the house is ceramic tile...

0.05(12592.80) = \$629.64

Total Flooring = \$(5624.64 + 943.68 + 455.40 + 629.64)

$\boxed{\text{Total Flooring} = \$7,653.36}$

14/14

Interior Doors: (p.114)

An average Post and Beam house uses hollow core interior doors which have the largest size 36" x 80". However, the Straw bale house design has interior doors of 36" x 24". There fore, this cost estimate will consider hollow core doors at 36" x 80" size...

Flush birch interior doors, Hollow core, 1-3/8" thick. wood veneer. Stainable + paintable, [illegible] wood stile and rail. (National Construction Estimator p.114)

36" x 80" = \$77.20/each

8 interior doors (\$77.20) = **\$617.60**

Interior Walls:

Gypsum Wallboard: (National Construction Estimator p.432)

Gypsum wallboard nailed or screwed to wood framing or wood furring, no taping or finishing included 3/8" on walls = \$0.56/sq ft.

Adding up all the square footage of the interior walls...

16' (1/2') = 8 ft²
11' (1/2') = 5.5
12' (1/2') = 6
10' (1/2') = 5
14' (1/2') = 7
12 (1/2') = 6
11' (1/2') = 5.5
5' (1/2') = 2.5
6' (1/2') = 3
4 (1/2') = 2
3 (1/2') = 1.5
8' (1/2') = 4
10' (1/2') = 5
8' (1/2') = 4
4' (1/2') = 2
10' (0.26') = 2.6
10' (0.26') = 2.6
18' (0.26) = 4.68

[illegible]

11/14

$76.88\ ft^2\left(\frac{\$0.56}{ft^2}\right) = \$43.05$

Stairs

Job-built Stairways (National Construction Estimator p.290)
using 2" Douglas Fir per MBF = $535.00

Windows (National Construction Estimator p.304)

Single-hung → 3'0" × 4'0" = $159 each

26 windows

26 ($159) = $4134.00

Exterior Doors: (National Construction Estimator p.104)

The straw bale house designed uses exterior doors of a 42" × 84" size. However, this could not be found so a 36" × 80" door was assumed for the estimate.

2 exterior doors

Wood Exterior Slab Doors = $102.20 each

2(102.20) = $204.40

Bathrooms: (RS Means Square Foot Costs 2008 p. 36)

Full Bath (including plumbing, wall and floor finishes) = $5129.0

2 Bathrooms × 5129.00 = $10,258.00

Half Bath (including plumbing, wall and floor finishes) =
$3107.00

12/14

Kitchen:

Sink: (Repair and Remodeling Cost Data 1997 p. 286)
counter top style 30"×21" = $430.00 each

$430.00

Water Heater: (Repair + Remodeling Cost Data 1997 p288)

40 gallon, electric water heater = $545.00 each

$545.00

Kitchen countertops:
(RS Means Square Foot Costs 2008 p.58)

Average stock plastic laminate, 24" wide
w/ backsplash = $23/L.F

Average counter space = 14 L.F.

$14 \text{ L.F.} \left(\frac{\$23}{\text{L.F.}}\right) = \$322$

Kitchen Cabinets:

(RS Means Square Foot Costs 2008 p. 58)

12" deep, 2 doors, 15" high, 33" wide = $237.00/Unit

$2 \text{ units} \left(\frac{\$237.00}{\text{Unit}}\right) = \$474.00$

13/14

Electrical:

Circuit Breakers:

(RS Means Repair + Remodeling Cost Data 1997 p. 319)

100 amp = $530 each

$530.00

Lighting Fixtures:

(RS Means Repair + Remodeling Cost Data 1997 p. 323)

Incandescent lighting = $435 each

7 lightings ($435) = $3045.00

Because the books that have been used are from previous years, the cost would be different than today. Therefore, a 3% increase is used for each year difference.

2003 information...

1.21 (984 + 3852) = $5851.56

2009 information...

1.03 (4471.20 + 2050 + 3725 + 1100 + 1096 + 306.12 + 7653.34 + 617.60 + 43.05 + 535 + 4134 + 204.40)

= $26713.80

1997 information...

1.39 (1857.10 + 430 + 545 + 530 + 3045) = $8905.87

2008 information...

1.06 (10,258 + 3107 + 322 + 474) = $15010.66

14/14

Total Cost:

(5851.56 + 26713.80 + 8905.87 + 15010.66 + 47736) =

\$104,217.89

Location Factor for Worcester, MA = 1.13

1.13 (104217.89) = \$117766.22

Mark up

To achieve a 20% mark up, add back 25% of the cost.

\$117766.22 (0.25) = \$29441.56

\$(117766.22 + 29441.56) = $\boxed{\$147207.78}$

Appendix G: Compressive Bale and Specimen Test Results (Printed Graphs)

Compression Test of Unplastered Bale – UB1

Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

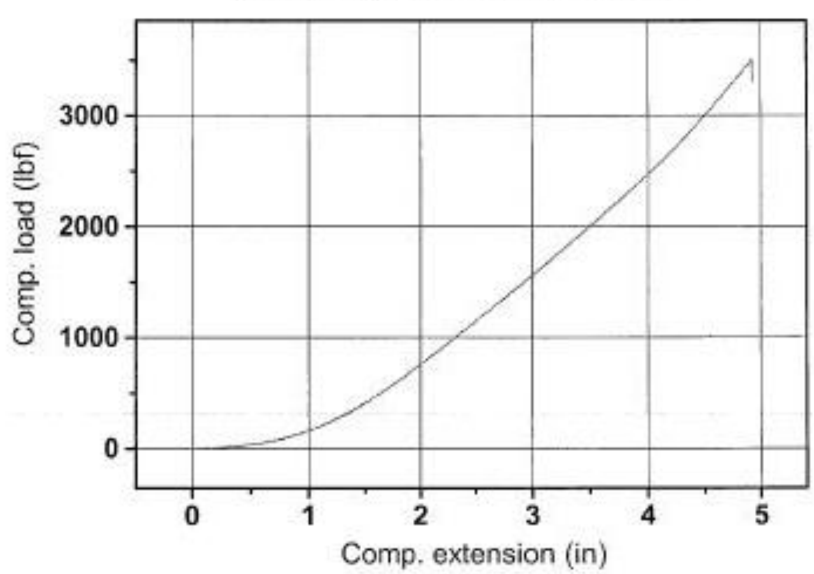
Company:	Straw Bale MQP	Name:		
Lab name:	WPI	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	12/14/10	Humidity:		
		Speed 1:	0.25	in/min

Note 1: Comp. of plain bale 12-14-10

Note 2:

Note 3:

ASTM General Compression Test



	Maximum Load (lbf)	Comp. Ext. (in)
1	3504.79	4.921
Mean	3504.79	4.921
S.D.	0.00	0.000
Minimum	3504.79	4.921
Maximum	3504.79	4.921
Range	0.00	0.000

Compression Test of Two-Sided, Earthen-Based Plastered Bale – EB2

Worc. Polytechnic Inst.

100 Institute Road

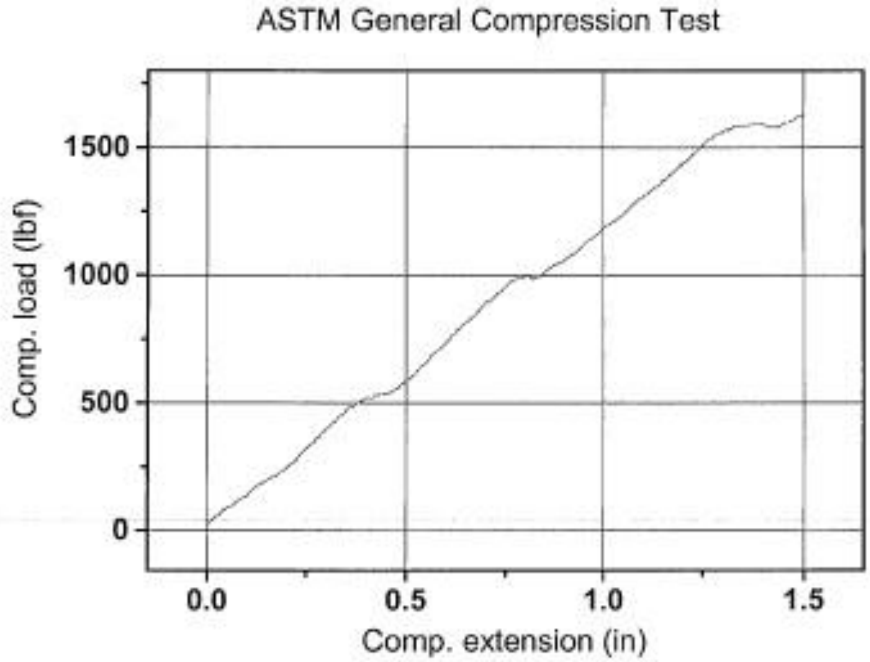
Worc. Mass. 01609

Company:	Straw Bale MQP	Name:		
Lab name:	WPI	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	12/14/10	Humidity:		
		Speed 1:	0.25	in/min

Note 1: Comp. 2 side plastered bale #1 12-14-10

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	1636.75	1.501
Mean	1636.75	1.501
S.D.	0.00	0.000
Minimum	1636.75	1.501
Maximum	1636.75	1.501
Range	0.00	0.000

Compression Test of Two-Sided, Earthen-Based Plastered Bale – EB3

Worc. Polytechnic Inst.

100 Institute Road

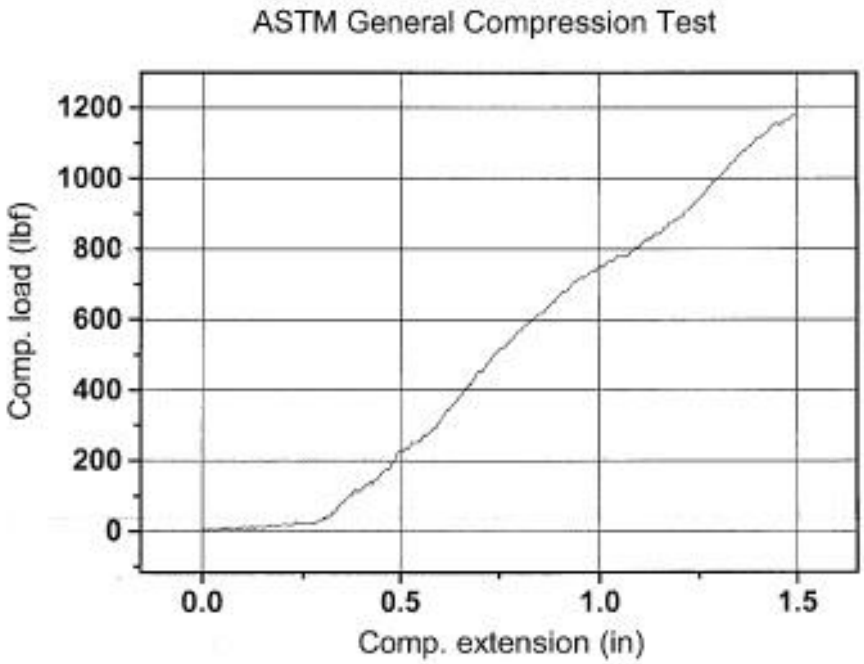
Worc. Mass. 01609

Company:	Straw Bale MQP	Name:		
Lab name:	WPI	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	12/14/10	Humidity:		
		Speed 1:	0.25	in/min

Note 1: Comp. 2 side plastered bale #2 12-14-10

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	1181.58	1.497
Mean	1181.58	1.497
S.D.	0.00	0.000
Minimum	1181.58	1.497
Maximum	1181.58	1.497
Range	0.00	0.000

Lateral Test of Two-Sided, Earthen-Based Plastered Bale – EB4

Worc. Polytechnic Inst.

100 Institute Road

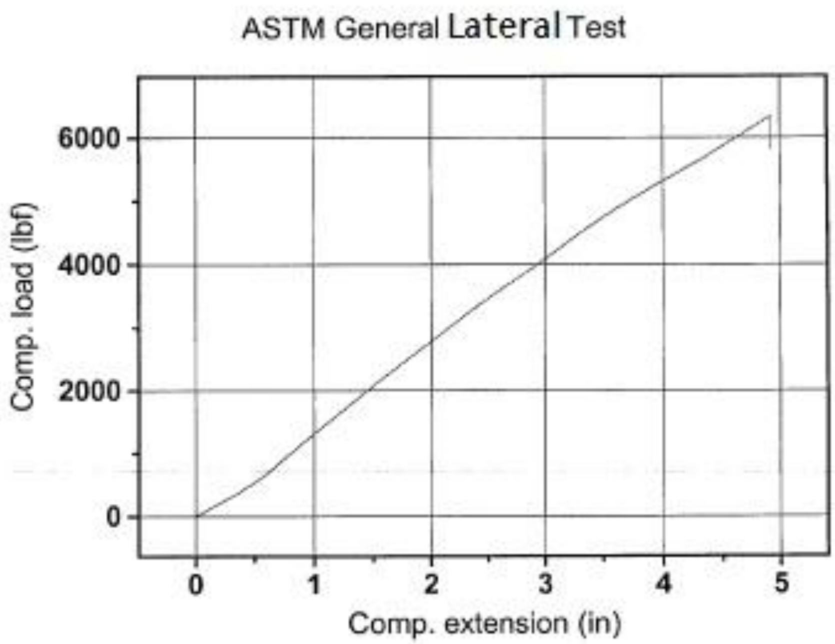
Worc. Mass. 01609

Company:	Straw Bale MQP	Name:		
Lab name:	WPI	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	12/15/10	Humidity:		
		Speed 1:	0.25	in/min

Note 1: Lateral. 2 side plastered bale #112-15-10

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	6336.93	4.919
Mean	6336.93	4.919
S.D.	0.00	0.000
Minimum	6336.93	4.919
Maximum	6336.93	4.919
Range	0.00	0.000

Shear Test of Two-Sided, Earthen-Based Plastered Bale – EB5

Worc. Polytechnic Inst.

I00 Institute Road

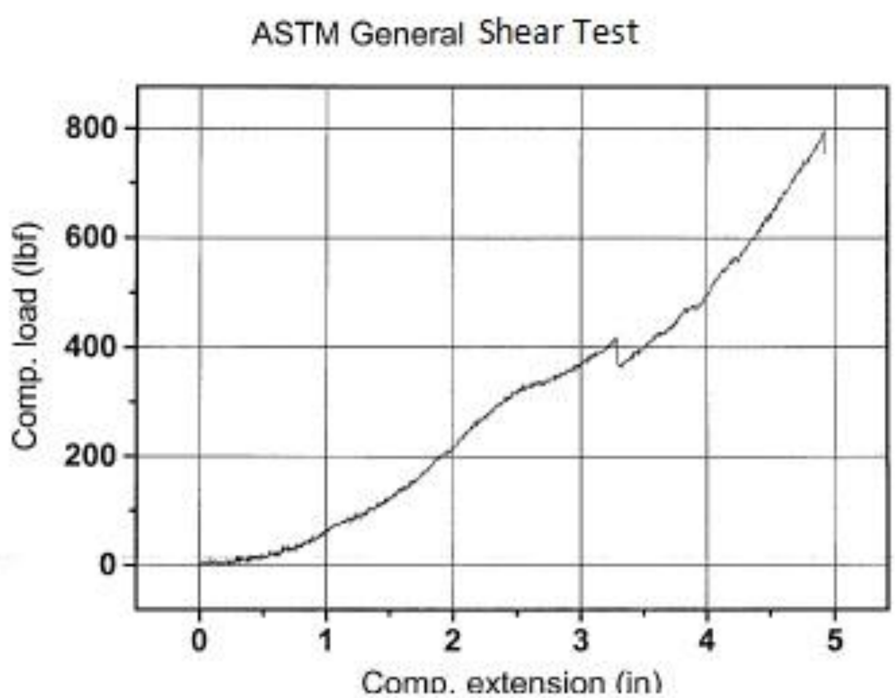
Worc. Mass. 01609

Company:	Straw Bale MQP	Name:		
Lab name:	WPI	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	12/21/10	Humidity:		
		Speed 1:	0.25	in/min

Note 1: Shear. 2 side plastered bale #1 12-21-10

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	796.33	4.921
Mean	796.33	4.921
S.D.	0.00	0.000
Minimum	796.33	4.921
Maximum	796.33	4.921
Range	0.00	0.000

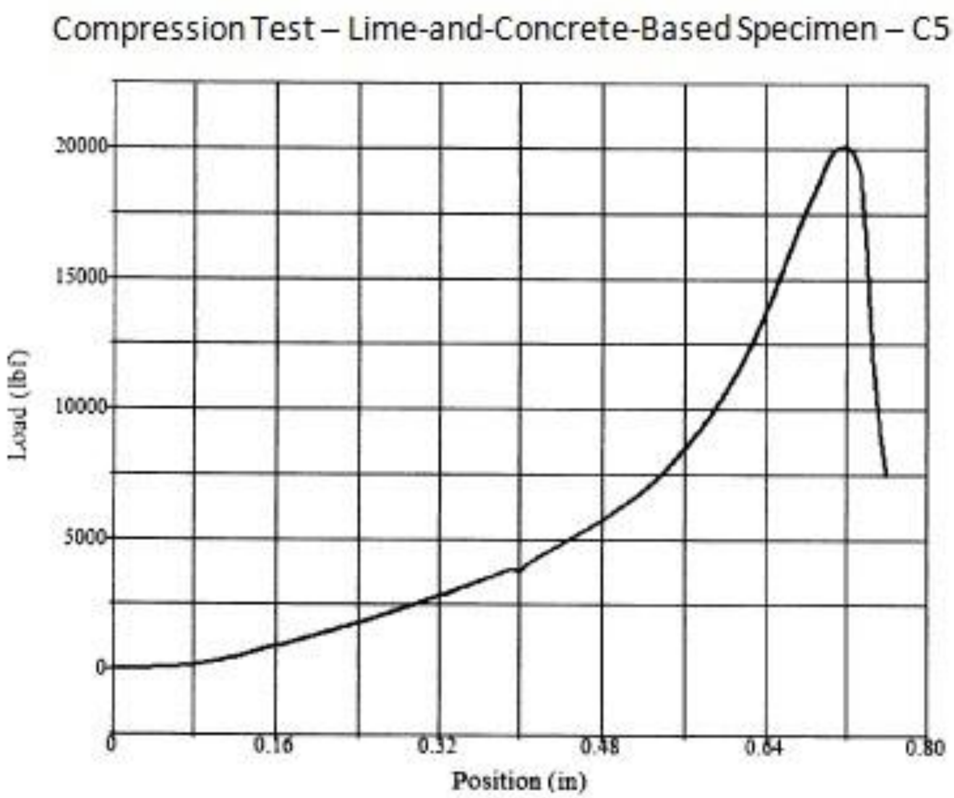
Compression Test of Lime-and-Concrete-Based Specimen – C5

Worc. Polytechnic Inst.

I00 Institute Road

Worc. Mass. 01609

CEINSTRON1596 11:23:16 AM 12/2/2010



Test Summary

Counter:	596
Elapsed Time:	00:01:28
Procedure Name:	3X6 Cylinder
Start Date:	12/2/2010
Start Time:	11:20:20 AM
End Date:	12/2/2010
End Time:	11:21:48 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Conctete
Comments:	LBC-1 Comp.

Test Results

Area:	7.0686 in²
Compressive Strength:	2835 psi
Peak Load:	20037 lbf
Diameter:	3.0000 in

Compression Test of Lime-and-Concrete-Based Specimen– C6

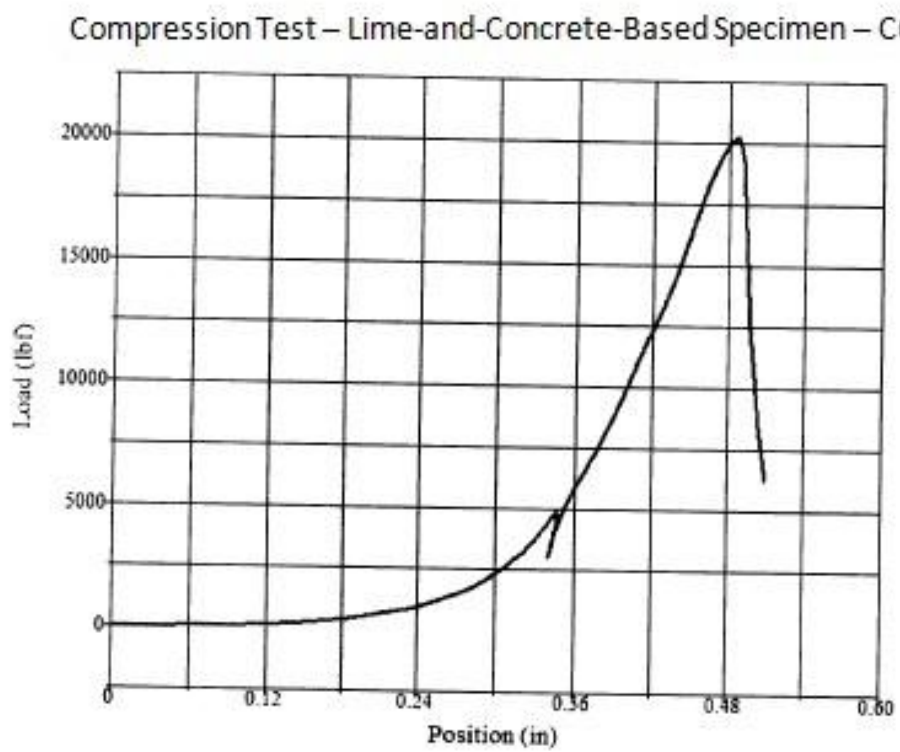
Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

CEINSTRON1597

11:29:08 AM 12/2/2010



Test Summary

Counter:	597
Elapsed Time:	00:01:27
Procedure Name:	3X6 Cylinder
Start Date:	12/2/2010
Start Time:	11:27:12 AM
End Date:	12/2/2010
End Time:	11:28:39 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Concrete
Comments:	LBS-2 Comp.

Test Results

Area:	7.0686 in^2
Compressive Strength:	2858 psi
Peak Load:	20199 lbf
Diameter:	3.0000 in

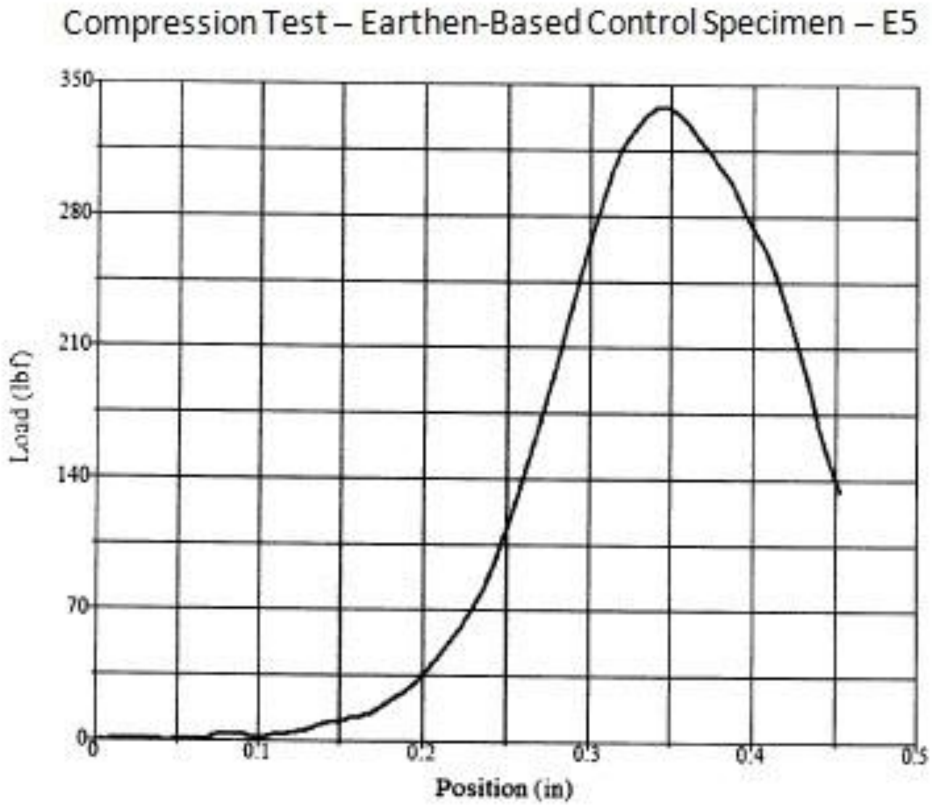
Compression Test of Earthen-Based Control Specimen (1st Batch) – E5

Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

CEINSTRON1602 11:22:28 AM 12/10/2010



Test Summary

Counter:	602
Elapsed Time:	00:00:11
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:22:09 AM
End Date:	12/10/2010
End Time:	11:22:20 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Control - 1A
Comments:	Compression

Test Results

Area:	7.0686 in^2
Compressive Strength:	48 psi
Peak Load:	338 lbf
Diameter:	3.0000 in

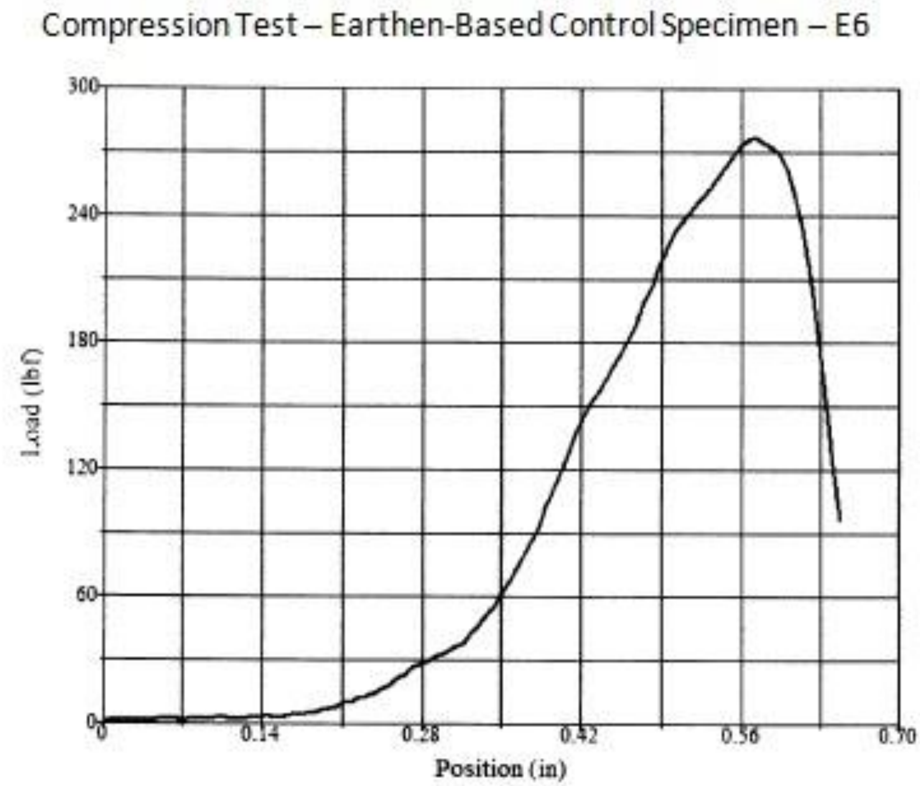
Compression Test of Earthen-Based Control Specimen (1st Batch) – E6

Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

CEINSTRON1603 11:24:21 AM 12/10/2010



Test Summary	
Counter:	603
Elapsed Time:	00:00:14
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:23:55 AM
End Date:	12/10/2010
End Time:	11:24:09 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Control - 1B
Comments:	Compression

Test Results	
Area:	7.0686 in²
Compressive Strength:	39 psi
Peak Load:	276 lbf
Diameter:	3.0000 in

Compression Test of Earthen-Based Control Specimen (2nd Batch) – E7

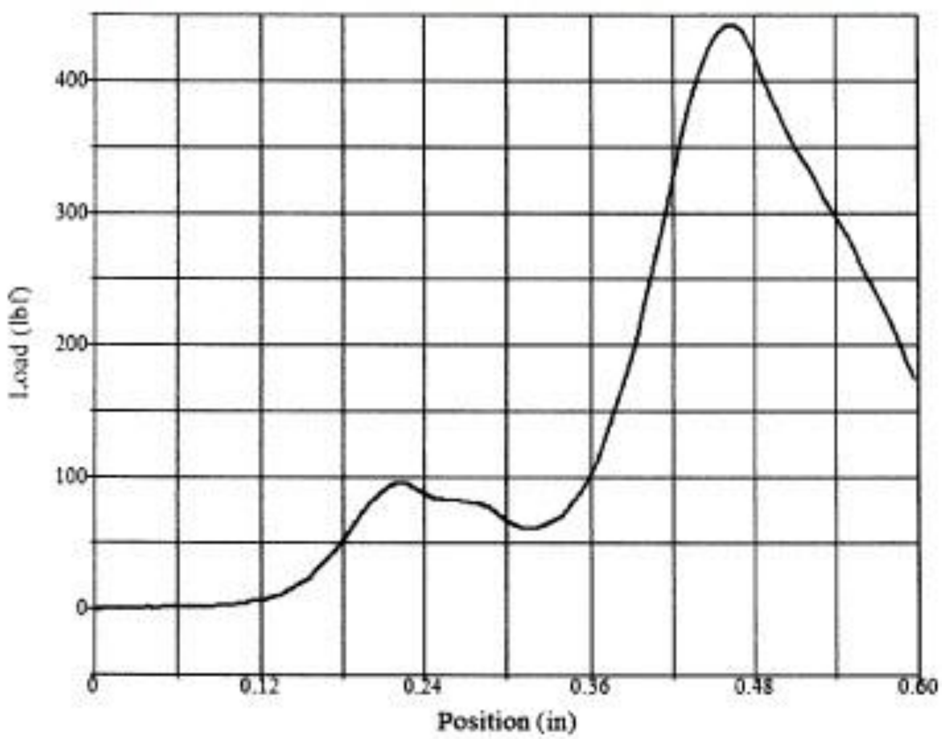
Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

CEINSTRON1604 11:26:25 AM 12/10/2010

Compression Test – Earthen-Based Control Specimen – E7



Test Summary

Counter:	604
Elapsed Time:	00:00:13
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:25:59 AM
End Date:	12/10/2010
End Time:	11:26:12 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	control 2a
Comments:	compression

Test Results

Area:	7.0686 in²
Compressive Strength:	63 psi
Peak Load:	442 lbf
Diameter:	3.0000 in

Compression Test of Earthen-Based Control Specimen (2nd Batch) – E8

Worc. Polytechnic Inst.

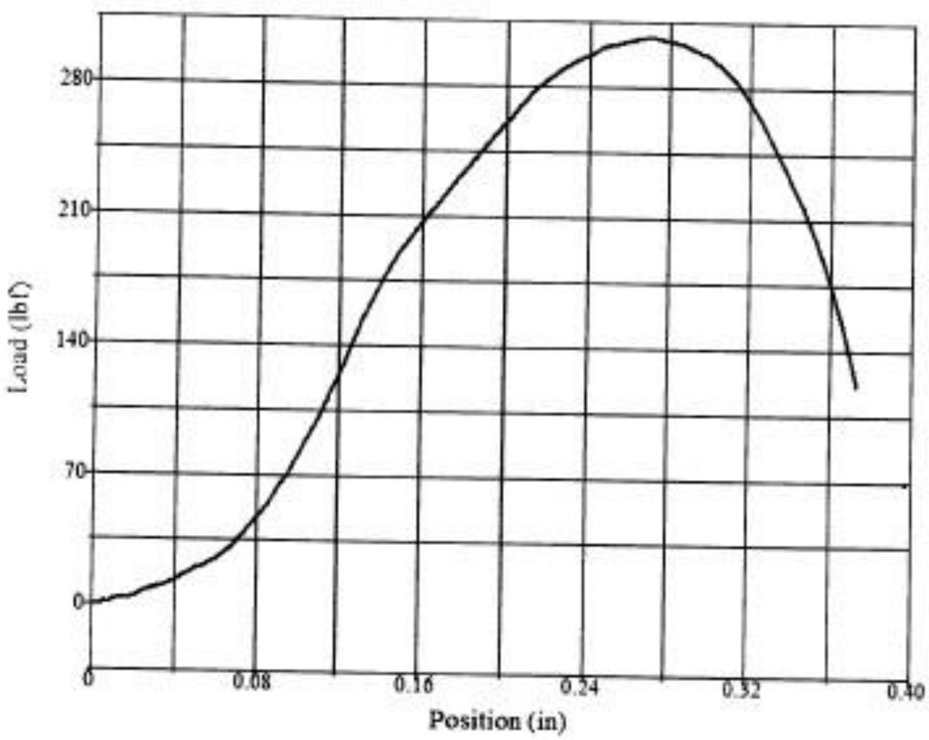
100 Institute Road

Worc. Mass. 01609

CEINSTRON1605

11:28:26 AM 12/10/2010

Compression Test – Earthen-Based Control Specimen – E8



Test Summary

Counter:	605
Elapsed Time:	00:00:09
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:28:10 AM
End Date:	12/10/2010
End Time:	11:28:19 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	control 2b
Comments:	compression

Test Results

Area:	7.0686 in^2
Compressive Strength:	43 psi
Peak Load:	306 lbf
Diameter:	3.0000 in

Compression Test of Lime Plaster Specimen – L3

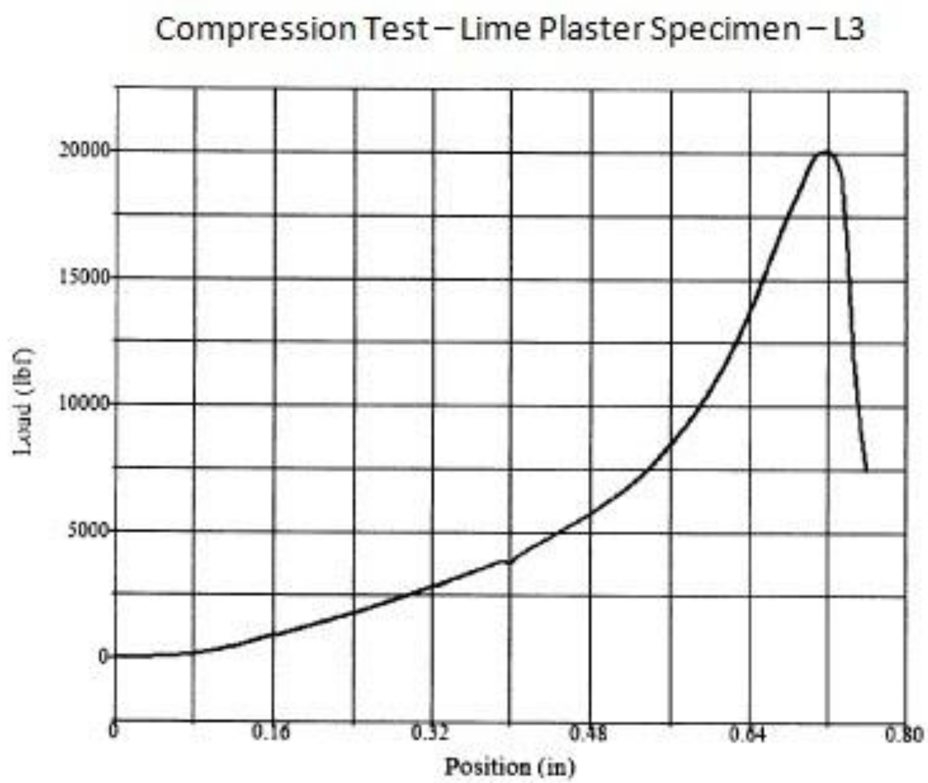
Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

CEINSTRON1596

11:23:16 AM 12/2/2010



Test Summary

Counter:	596
Elapsed Time:	00:01:28
Procedure Name:	3X6 Cylinder
Start Date:	12/2/2010
Start Time:	11:20:20 AM
End Date:	12/2/2010
End Time:	11:21:48 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Conetete
Comments:	LBC-1 Comp.

Test Results

Area:	7.0686 in^2
Compressive Strength:	2835 psi
Peak Load:	20037 lbf
Diameter:	3.0000 in

Compression Test of Lime Plaster Specimen – L4

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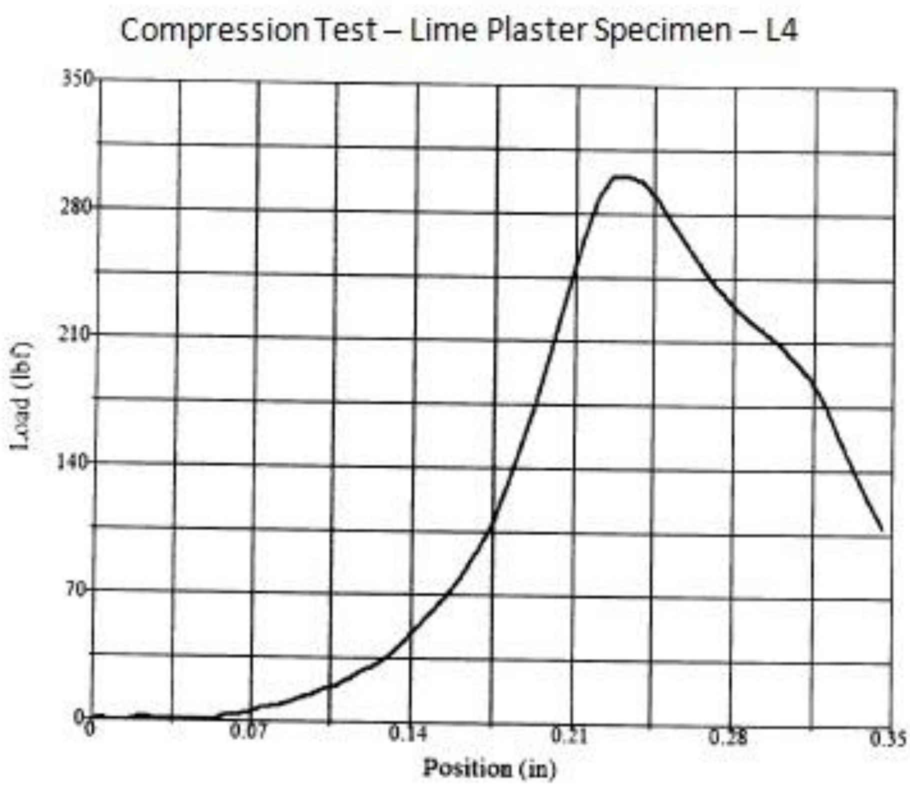
CEINSTRON1601

11:20:43 AM 12/10/2010



Test Summary

Counter:	601
Elapsed Time:	00:00:09
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:20:26 AM
End Date:	12/10/2010
End Time:	11:20:35 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Lime-4
Comments:	Compression

Test Results

Area:	7.0686 in^2
Compressive Strength:	43 psi
Peak Load:	301 lbf
Diameter:	3.0000 in

Compression Test of 10% Manure-to-Mix Specimen – 4C

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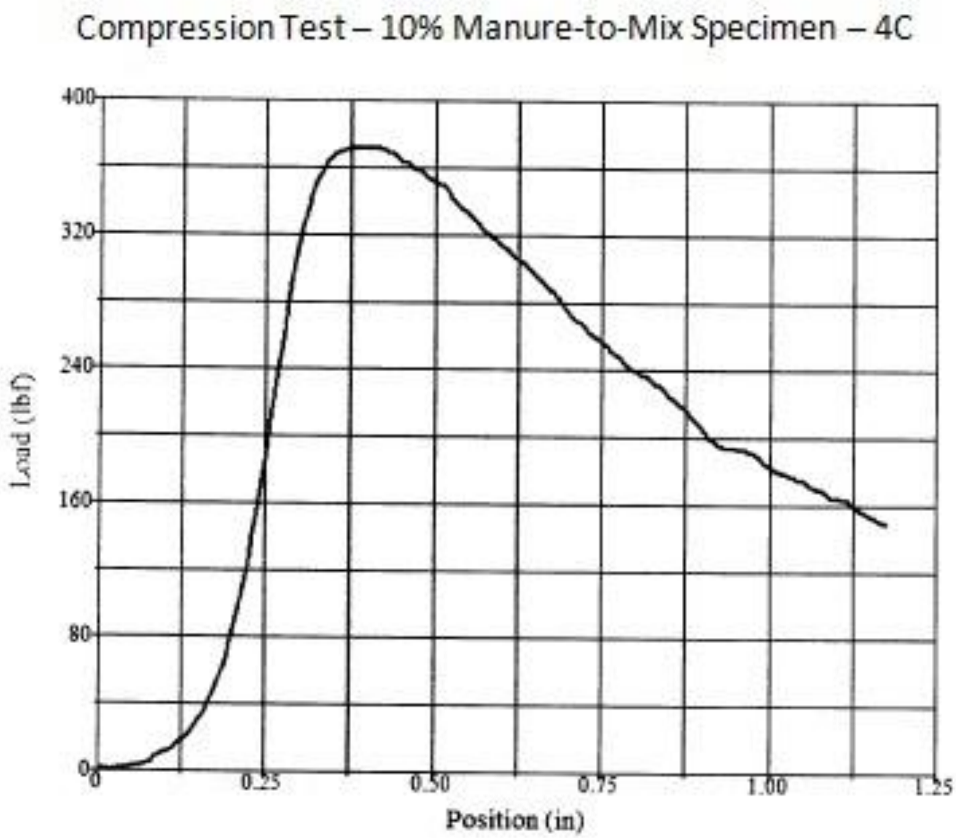
Worc. Mass. 01609

CEINSTRON1610

11:39:45 AM 12/10/2010



Test Summary

Counter:	610
Elapsed Time:	00:00:22
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:39:18 AM
End Date:	12/10/2010
End Time:	11:39:40 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	4C
Comments:	Compression

Test Results

Area:	7.0686 in^2
Compressive Strength:	53 psi
Peak Load:	372 lbf
Diameter:	3.0000 in

Compression Test of 25% Manure-to-Mix Specimen – 5C

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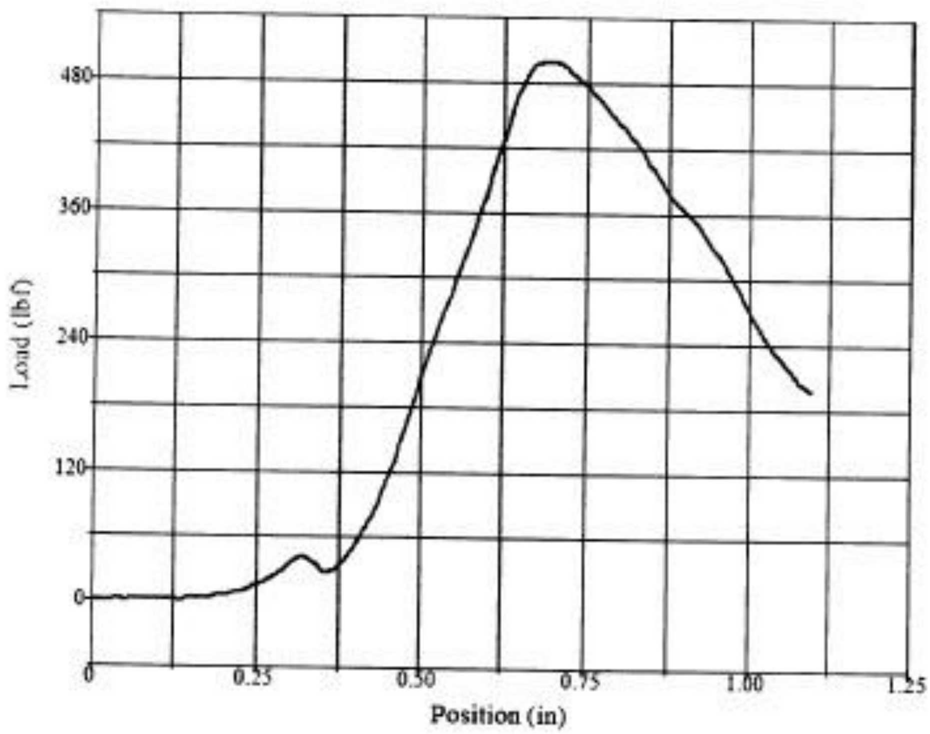
CEINSTRON1606 11:30:29 AM 12/10/2010

Compression Test - 25% Manure-to-Mix Specimen – 5C



Test Summary

Counter:	606
Elapsed Time:	00:00:20
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:29:59 AM
End Date:	12/10/2010
End Time:	11:30:19 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	5C
Comments:	commpression

Test Results

Area:	7.0686 in²
Compressive Strength:	71 psi
Peak Load:	499 lbf
Diameter:	3.0000 in

Compression Test of 25% Manure-to-Mix Specimen – 5D

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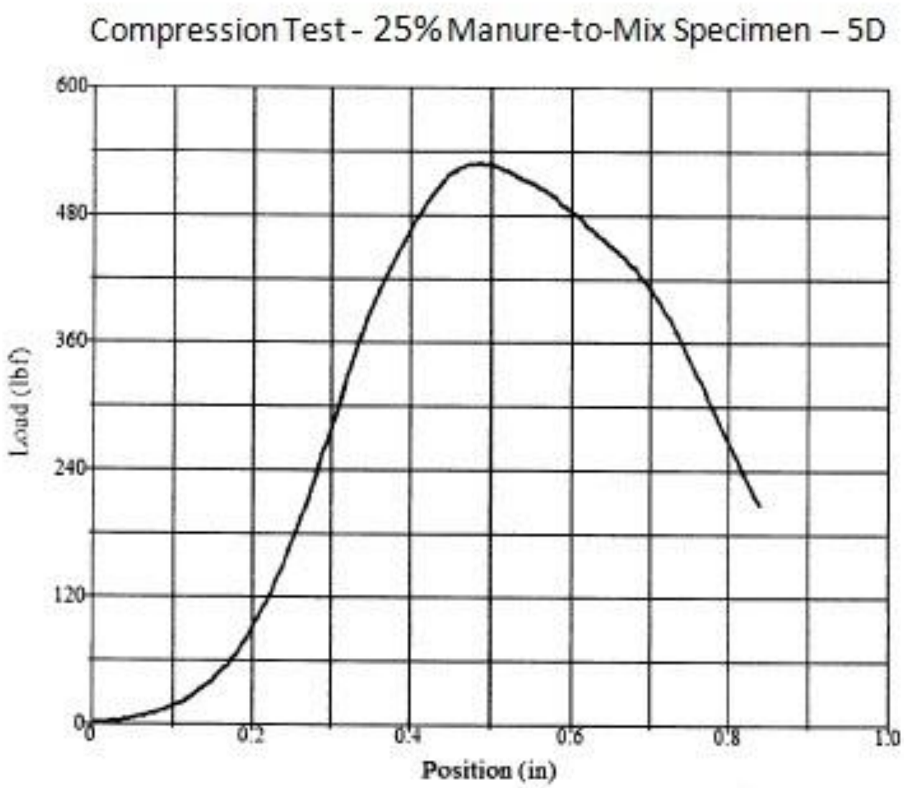
CEINSTRON1607 11:32:36 AM 12/10/2010



Test Summary	
Counter:	607
Elapsed Time:	00:00:17
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:32:12 AM
End Date:	12/10/2010
End Time:	11:32:29 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	5D
Comments:	compression

Test Results	
Area:	7.0686 in²
Compressive Strength:	75 psi
Peak Load:	528 lbf
Diameter:	3.0000 in

Compression Test of 40% Manure-to-Mix Specimen – 6C

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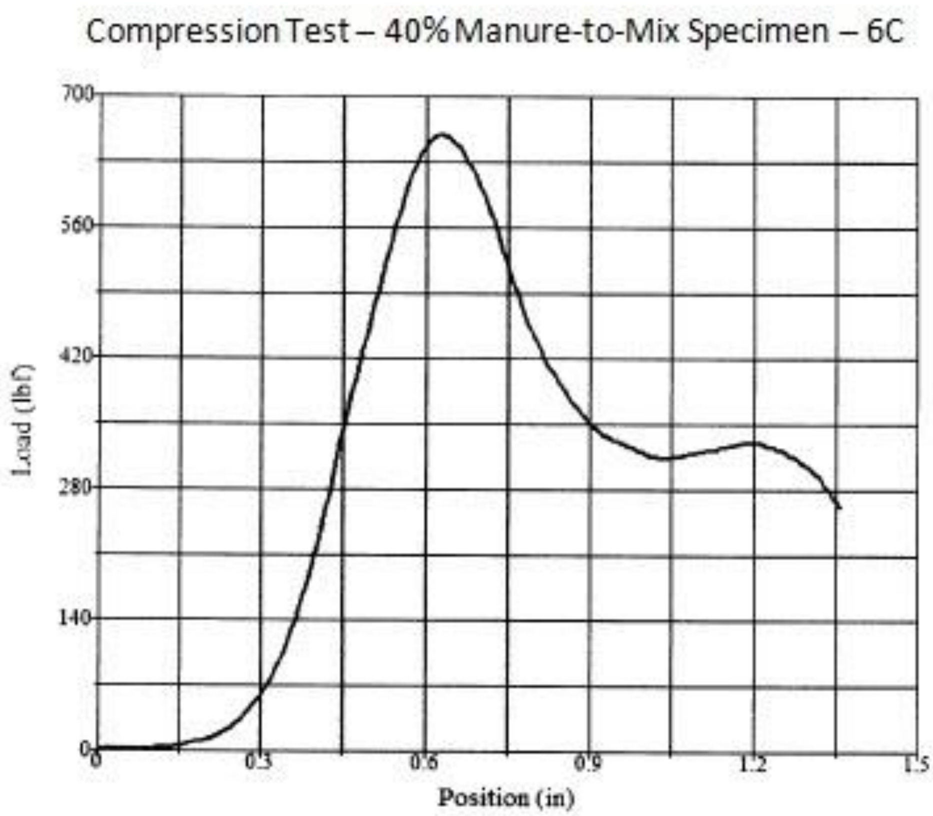
CEINSTRON1608 11:35:11 AM 12/10/2010



Test Summary

Counter:	608
Elapsed Time:	00:00:23
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:33:57 AM
End Date:	12/10/2010
End Time:	11:34:20 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	6C
Comments:	compression

Test Results

Area:	12.5664 in²
Compressive Strength:	52 psi
Peak Load:	658 lbf
Diameter:	4.0000 in

Compression Test of 40% Manure-to-Mix Specimen – 6D

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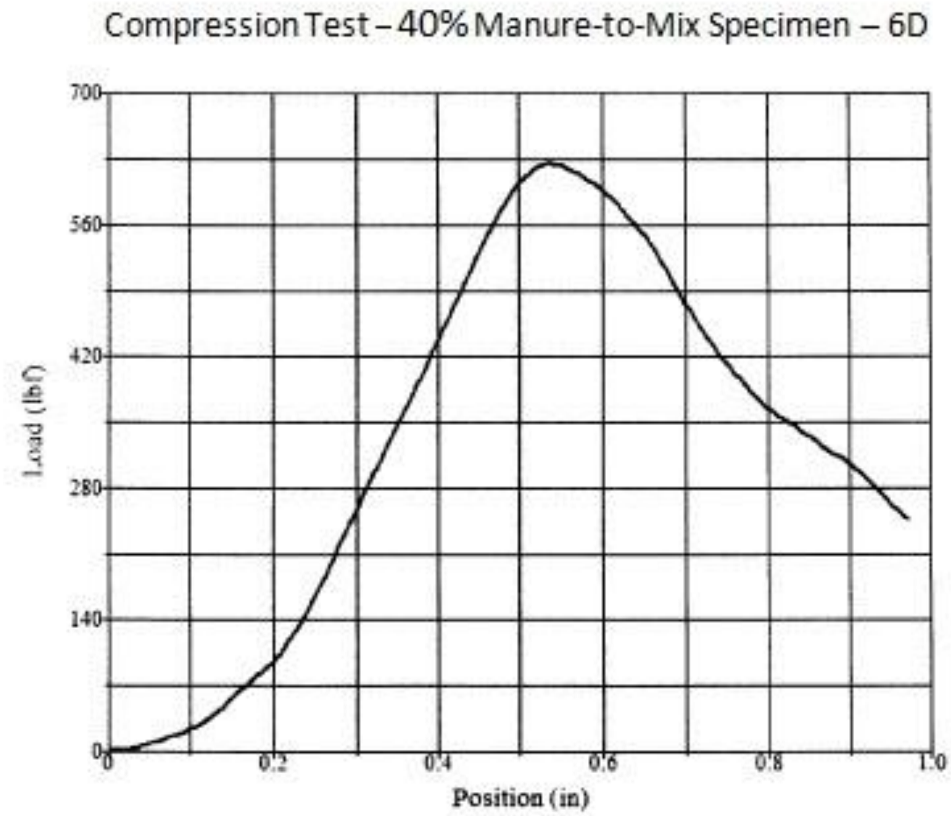
CEINSTRON1609 11:37:46 AM 12/10/2010



Test Summary

Counter:	609
Elapsed Time:	00:00:19
Procedure Name:	3X6 Cylinder
Start Date:	12/10/2010
Start Time:	11:37:21 AM
End Date:	12/10/2010
End Time:	11:37:40 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	6D
Comments:	compression

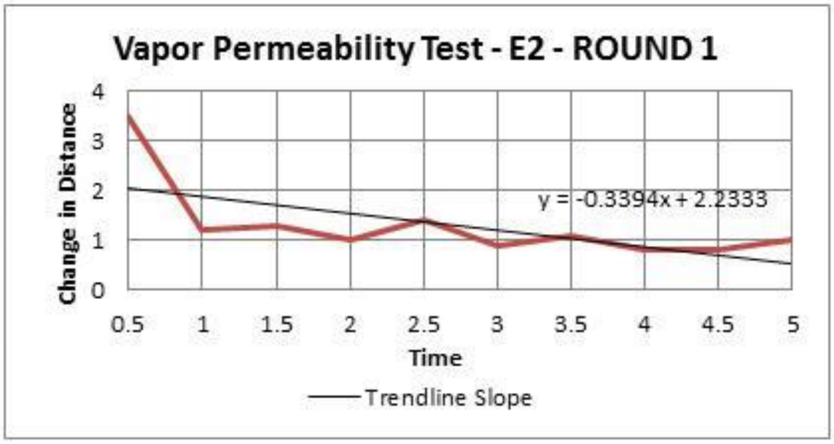
Test Results

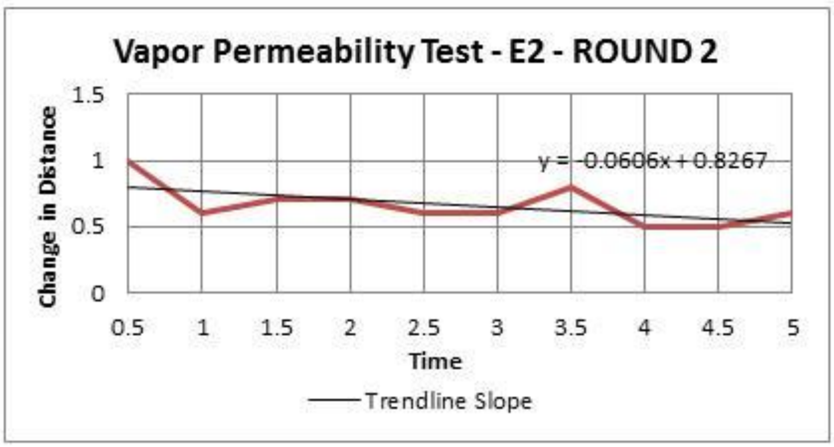
Area:	7.0686 in²
Compressive Strength:	88 psi
Peak Load:	624 lbf
Diameter:	3.0000 in

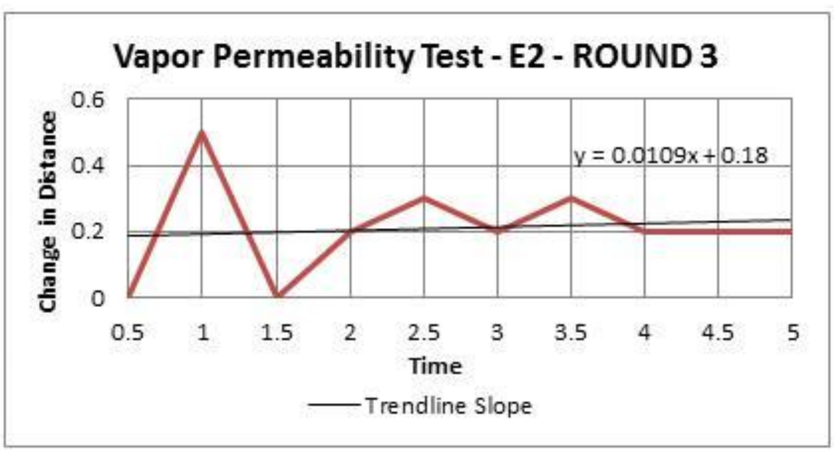
Appendix H: Vapor Permeability Test Results

Vapor Permeability Test of Earthen-Based Control Specimen – E2

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
E2	1	0		41
		0.5	3.5	37.5
		1	1.2	36.3
		1.5	1.3	35
		2	1	34
		2.5	1.4	32.6
		3	0.9	31.7
		3.5	1.1	30.6
		4	0.8	29.8
		4.5	0.8	29
		5	1	28
	2	0		42
		0.5	1	41
		1	0.6	40.4
		1.5	0.7	39.7
		2	0.7	39
		2.5	0.6	38.4
		3	0.6	37.8
		3.5	0.8	37
		4	0.5	36.5
		4.5	0.5	36
		5	0.6	35.4
	3	0		42.5
		0.5	0	42.5
		1	0.5	42
		1.5	0	42
		2	0.2	41.8
		2.5	0.3	41.5
		3	0.2	41.3
		3.5	0.3	41
		4	0.2	40.8
		4.5	0.2	40.6
		5	0.2	40.4

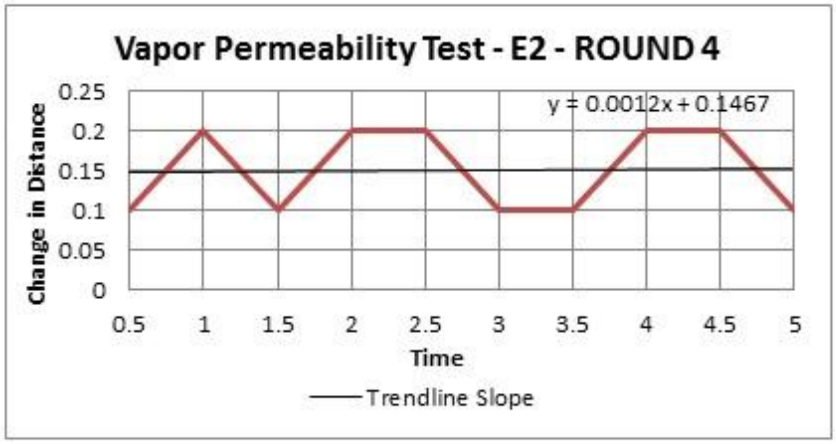


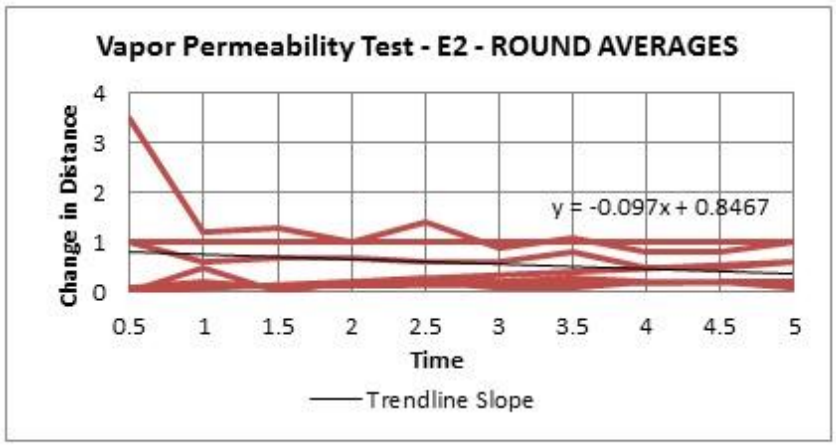




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
E2	4	0		40.4
		0.5	0.1	40.3
		1	0.2	40.1
		1.5	0.1	40
		2	0.2	39.8
		2.5	0.2	39.6
		3	0.1	39.5
		3.5	0.1	39.4
		4	0.2	39.2
		4.5	0.2	39
		5	0.1	38.9

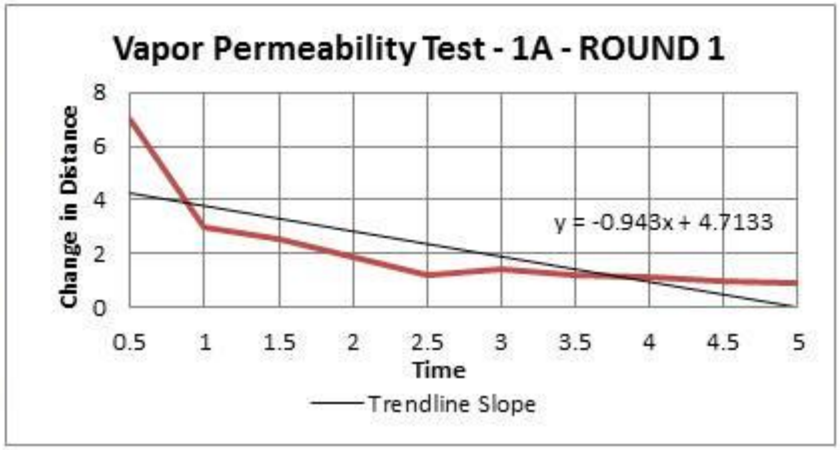
TOTAL Δ D = 23.2

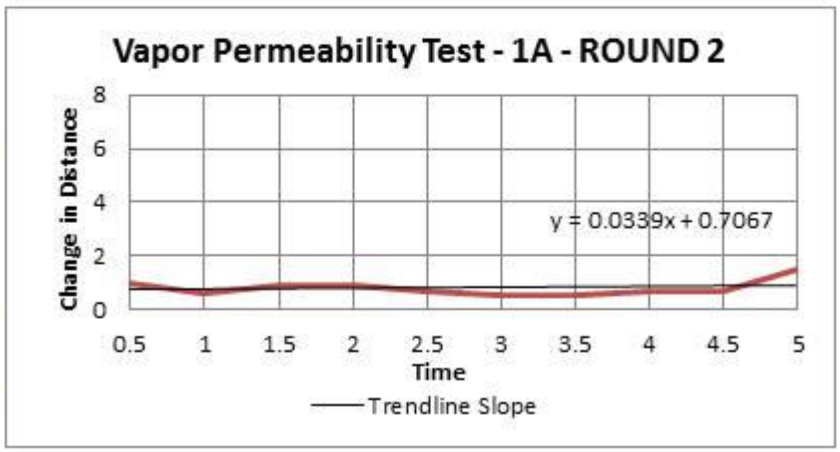


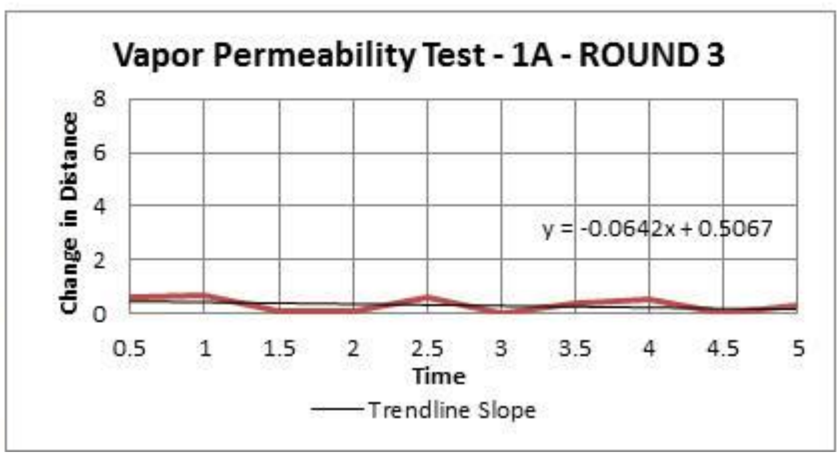


Vapor Permeability Test of 10% Lime-to-Clay Specimen– 1A

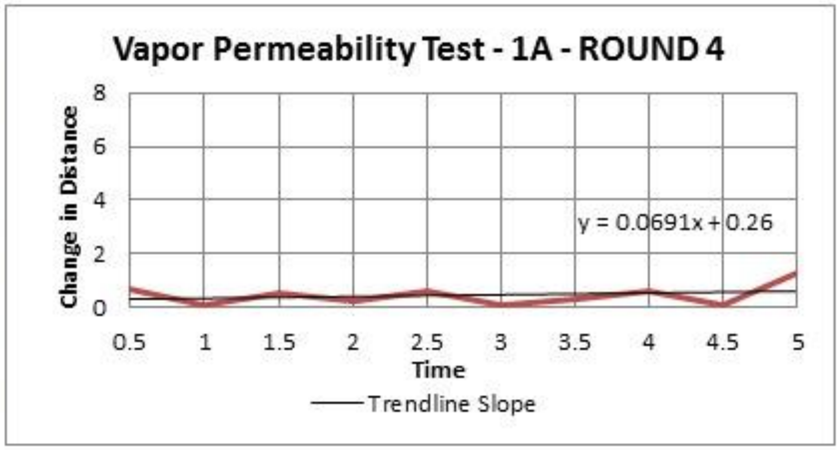
Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
1A	1	0		63
		0.5	7	56
		1	3	53
		1.5	2.5	50.5
		2	1.9	48.6
		2.5	1.2	47.4
		3	1.4	46
		3.5	1.2	44.8
		4	1.1	43.7
		4.5	1	42.7
		5	0.9	41.8
	2	0		41
		0.5	1	40
		1	0.6	39.4
		1.5	0.9	38.5
		2	0.9	37.6
		2.5	0.7	36.9
		3	0.5	36.4
		3.5	0.5	35.9
		4	0.7	35.2
		4.5	0.7	34.5
		5	1.5	33
	3	0		32
		0.5	0.6	31.4
		1	0.7	30.7
		1.5	0.1	30.6
		2	0.1	30.5
		2.5	0.6	29.9
		3	0	29.9
		3.5	0.4	29.5
		4	0.5	29
		4.5	0	29
		5	0.3	28.7

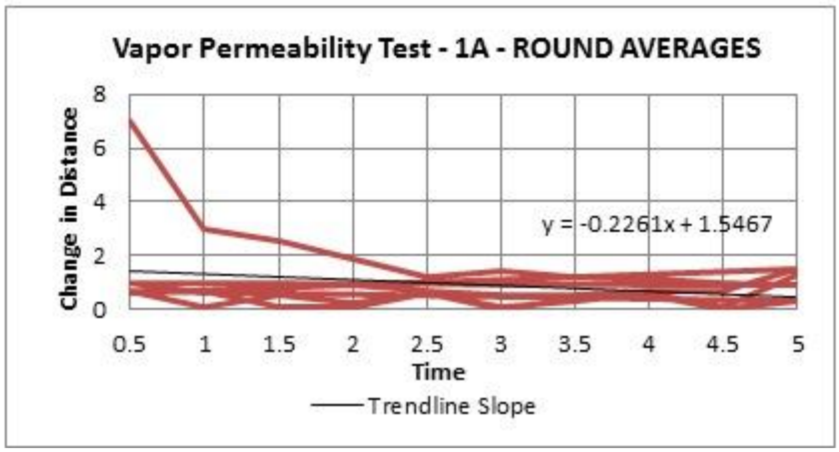






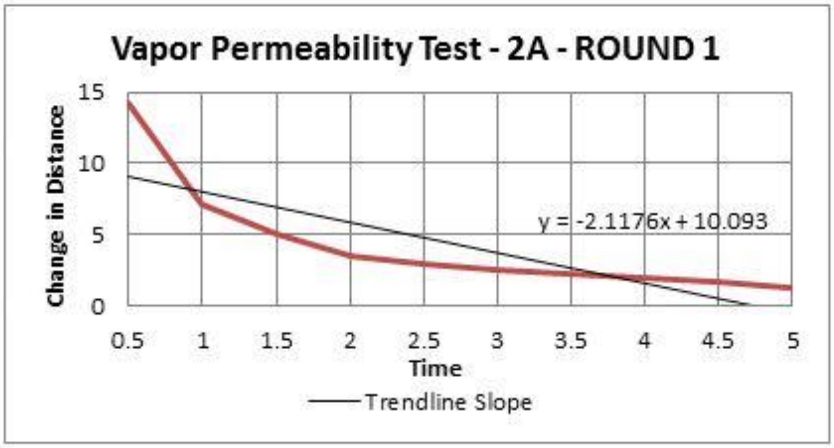
Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
A	4	0		28
		0.5	0.7	27.3
		1	0.1	27.2
		1.5	0.5	26.7
		2	0.2	26.5
		2.5	0.6	25.9
		3	0.1	25.8
		3.5	0.3	25.5
		4	0.6	24.9
		4.5	0.1	24.8
		5	1.3	23.5
		TOTAL Δ D =	37	

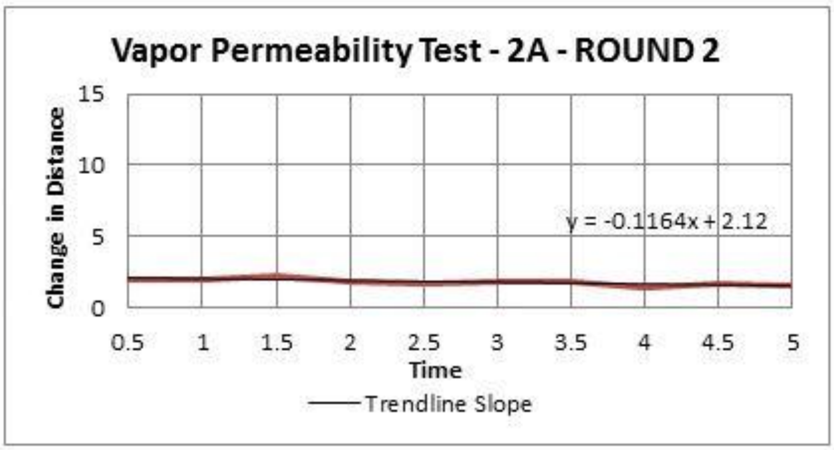


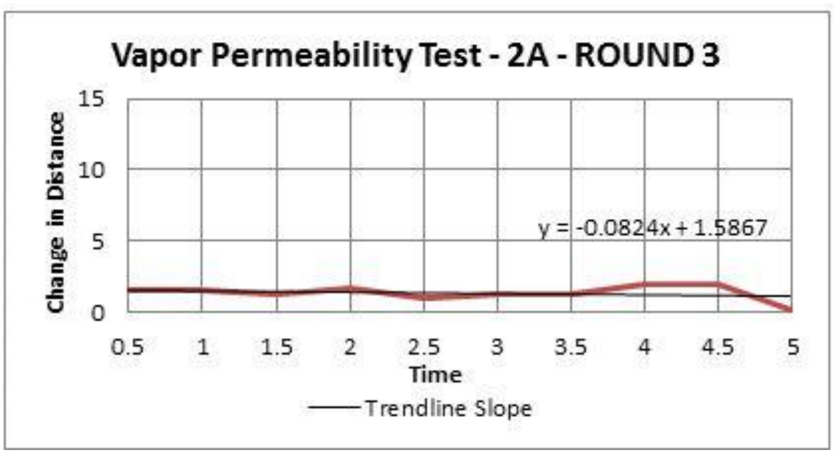


Vapor Permeability Test of 30% Lime-to-Clay Specimen – 2A

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
2A	1	0		64
		0.5	14.2	49.8
		1	7.2	42.6
		1.5	5.1	37.5
		2	3.5	34
		2.5	3	31
		3	2.5	28.5
		3.5	2.3	26.2
		4	1.9	24.3
		4.5	1.7	22.6
		5	1.3	21.3
	2	0		66
		0.5	2	64
		1	2	62
		1.5	2.2	59.8
		2	1.8	58
		2.5	1.7	56.3
		3	1.8	54.5
		3.5	1.8	52.7
		4	1.4	51.3
		4.5	1.7	49.6
		5	1.6	48
	3	0		47
		0.5	1.5	45.5
		1	1.5	44
		1.5	1.3	42.7
		2	1.7	41
		2.5	1	40
		3	1.3	38.7
		3.5	1.2	37.5
		4	2	35.5
		4.5	2	33.5
		5	0.1	33.4

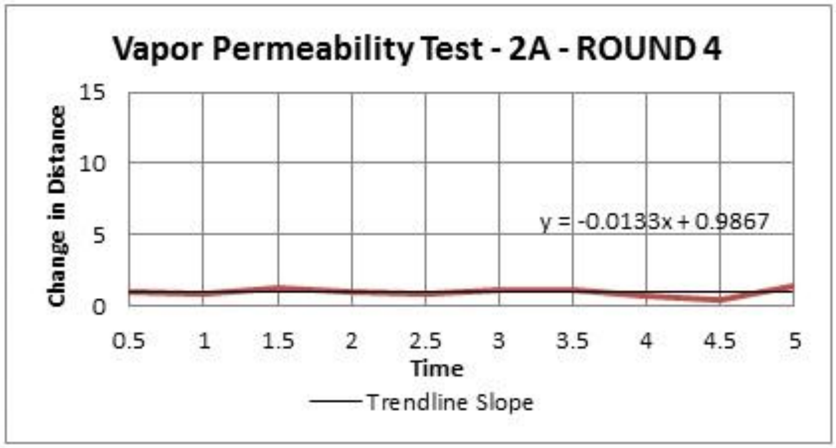


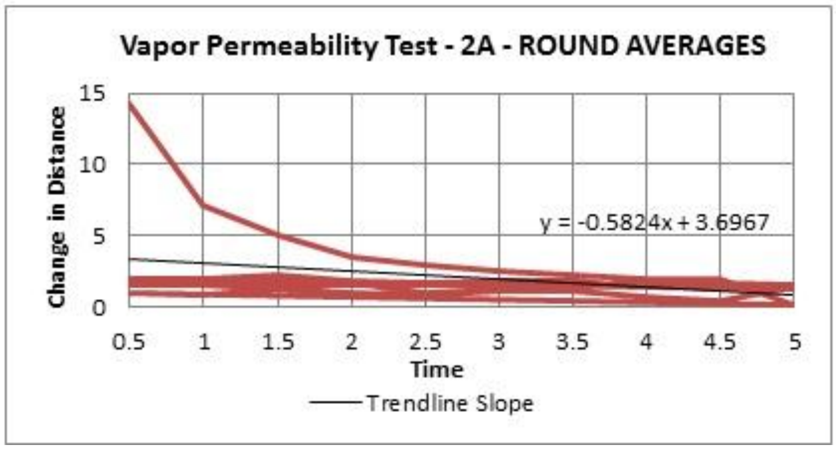




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
2A	4	0		31
		0.5	1	30
		1	0.8	29.2
		1.5	1.2	28
		2	1	27
		2.5	0.8	26.2
		3	1.1	25.1
		3.5	1.1	24
		4	0.7	23.3
		4.5	0.4	22.9
		5	1.4	21.5

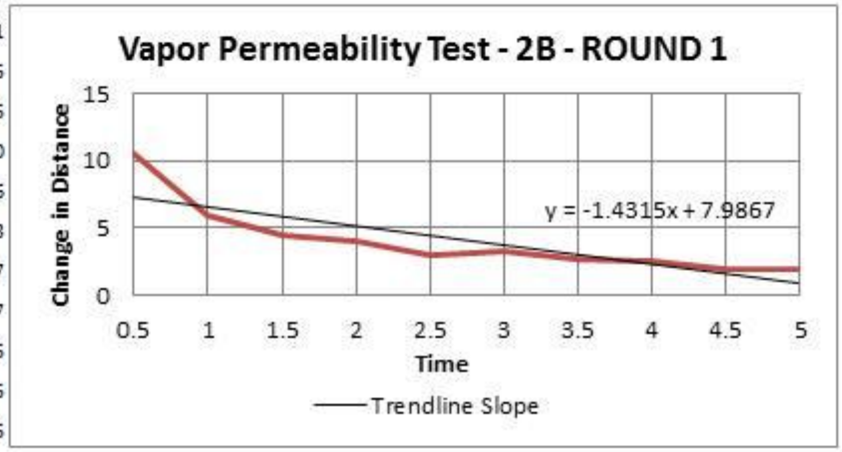
TOTAL Δ D = 83.8

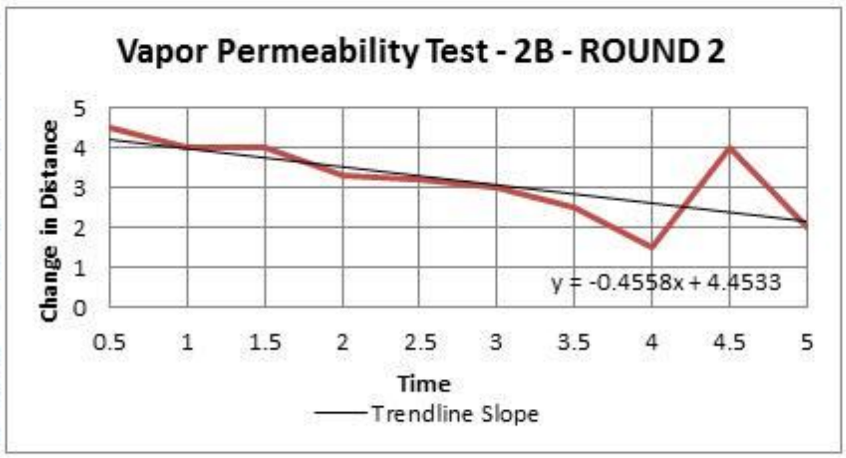


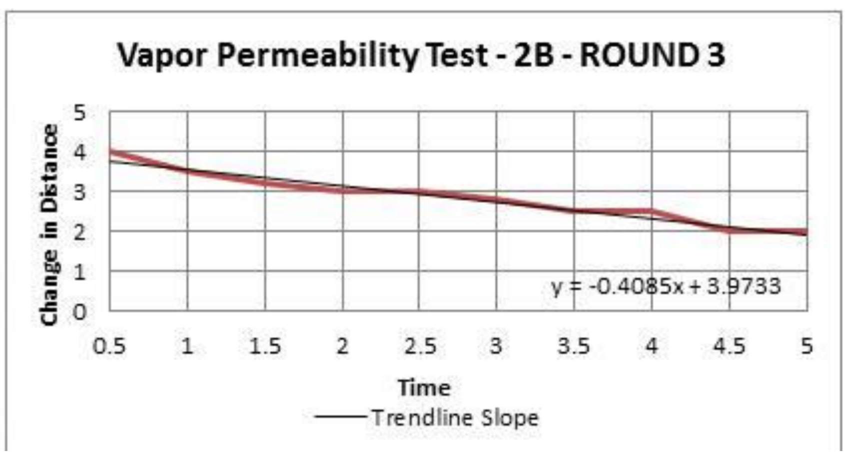


Vapor Permeability Test of 30% Lime-to-Clay Specimen – 2B

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
2B	1	0		41
		0.5	10.5	30.5
		1	6	24.5
		1.5	4.5	20
		2	4	16
		2.5	3	13
		3	3.3	9.7
		3.5	2.7	7
		4	2.5	4.5
		4.5	2	2.5
		5	2	0.5
	2	0		41.5
		0.5	4.5	37
		1	4	33
		1.5	4	29
		2	3.3	25.7
		2.5	3.2	22.5
		3	3	19.5
		3.5	2.5	17
		4	1.5	15.5
		4.5	4	11.5
		5	2	9.5
	3	0		42
		0.5	4	38
		1	3.5	34.5
		1.5	3.2	31.3
		2	3	28.3
		2.5	3	25.3
		3	2.8	22.5
		3.5	2.5	20
		4	2.5	17.5
		4.5	2	15.5
		5	2	13.5

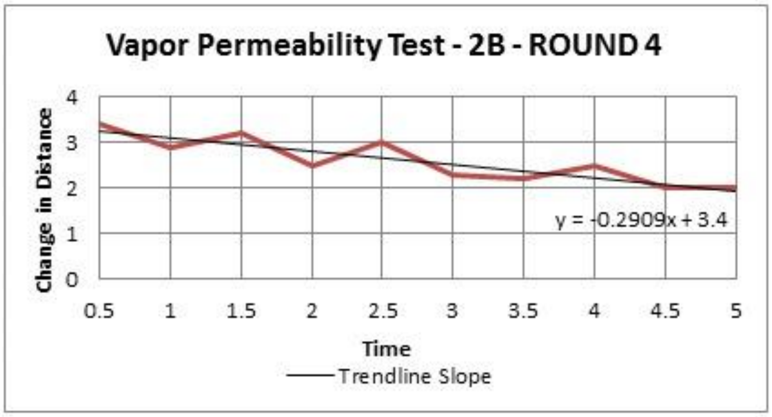


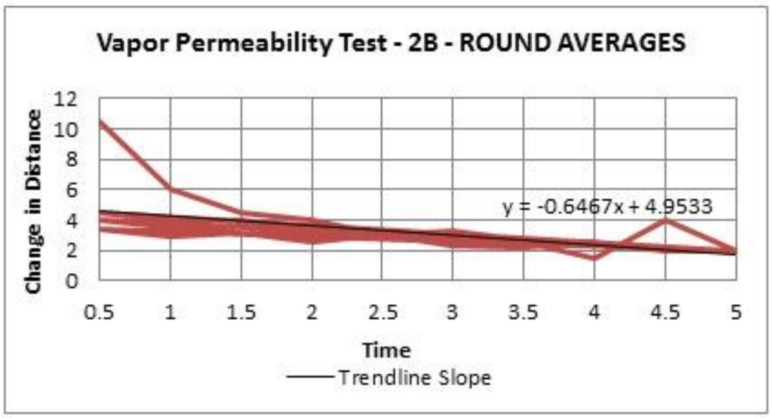




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
2B	4	0		41
		0.5	3.4	37.6
		1	2.9	34.7
		1.5	3.2	31.5
		2	2.5	29
		2.5	3	26
		3	2.3	23.7
		3.5	2.2	21.5
		4	2.5	19
		4.5	2	17
		5	2	15

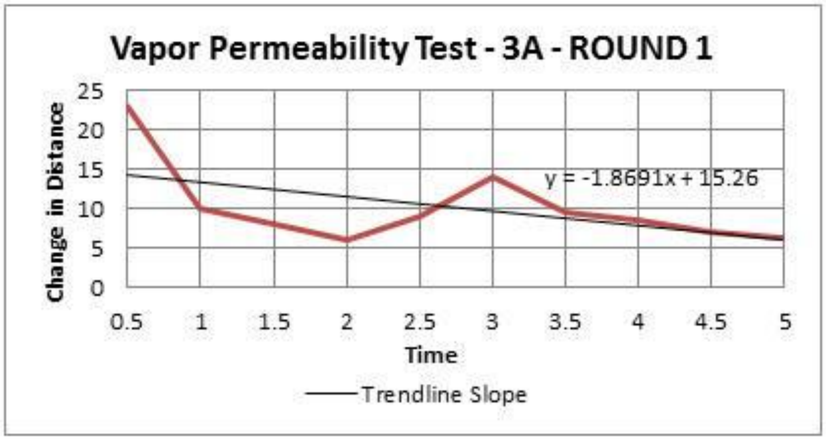
TOTAL Δ D = 127

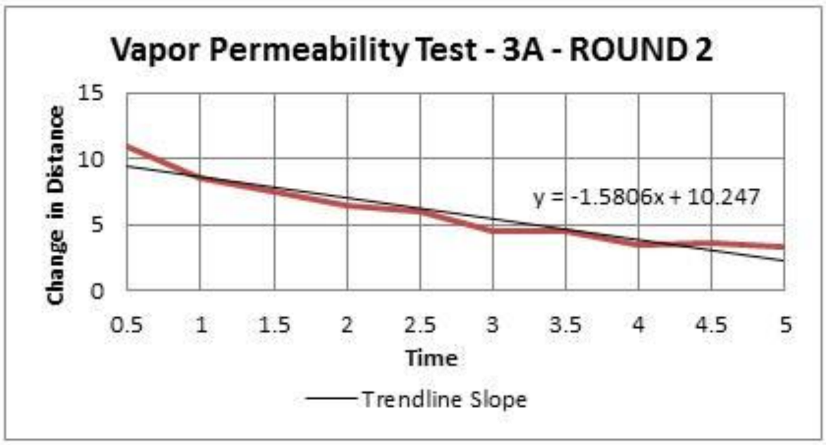


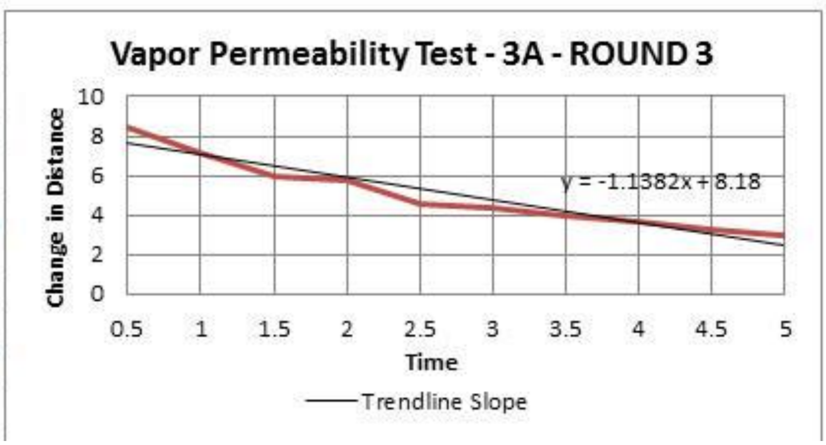


Vapor Permeability Test of 50% Lime-to-Clay Specimen – 3A

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
3a	1	0	0	50
		0.5	23	27
		1	10	17
		1.5	8	9
		2	6	3
		2.5	9	58.9
		3	14	45
		3.5	9.5	35.5
		4	8.5	27
		4.5	7	20
		5	6.2	13.8
	2	0	0	61.5
		0.5	11	50.5
		1	8.5	42
		1.5	7.5	34.5
		2	6.5	28
		2.5	6	22
		3	4.5	17.5
		3.5	4.5	13
		4	3.5	9.5
		4.5	3.7	5.8
		5	3.3	2.5
	3	0	0	64
		0.5	8.5	55.5
		1	7.2	48.3
		1.5	6	42.3
		2	5.8	36.5
		2.5	4.6	31.9
		3	4.4	27.5
		3.5	4	23.5
		4	3.7	19.8
		4.5	3.3	16.5
		5	3	13.5

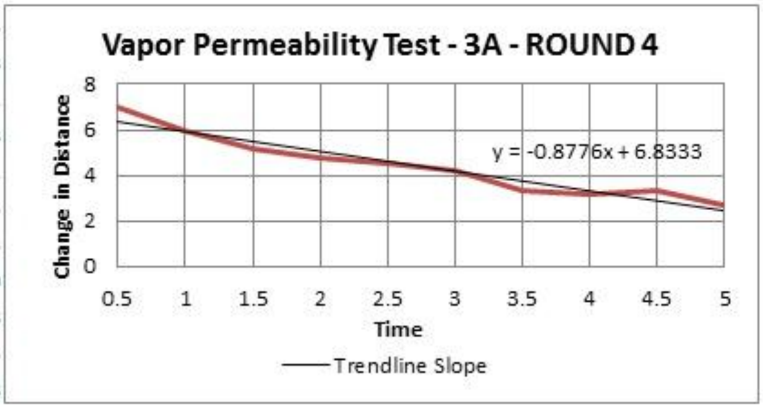


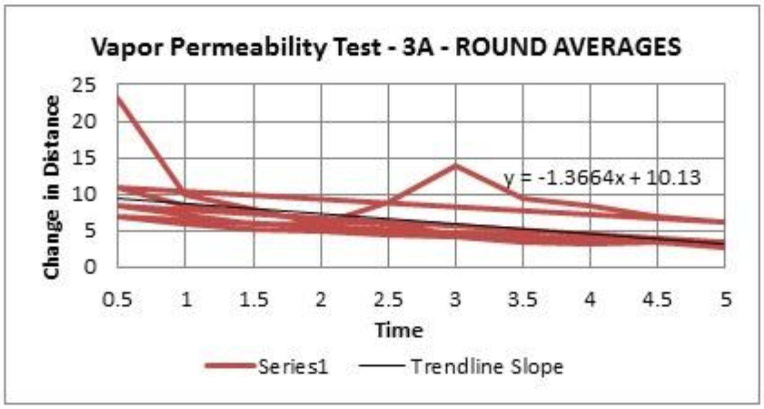




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
3A	4	0	0	65
		0.5	7	58
		1	6	52
		1.5	5.2	46.8
		2	4.8	42
		2.5	4.5	37.5
		3	4.2	33.3
		3.5	3.3	30
		4	3.2	26.8
		4.5	3.3	23.5
		5	2.7	20.8

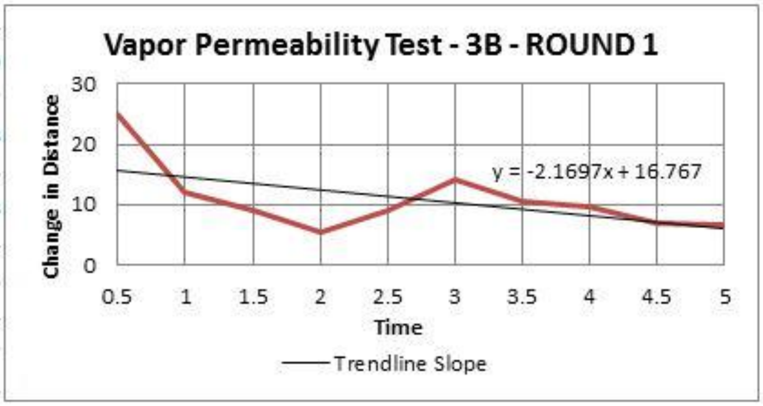
TOTAL Δ D = 254.9

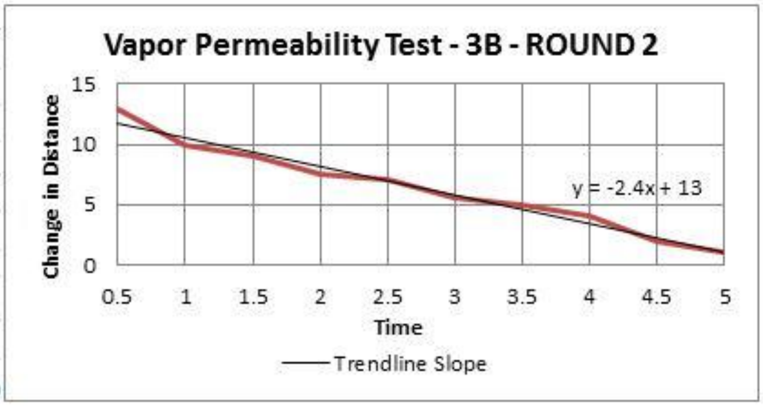


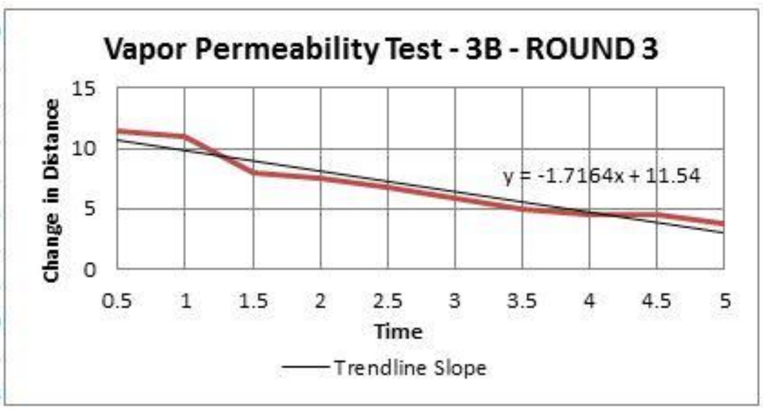


Vapor Permeability Test of 50% Lime-to-Clay Specimen – 3B

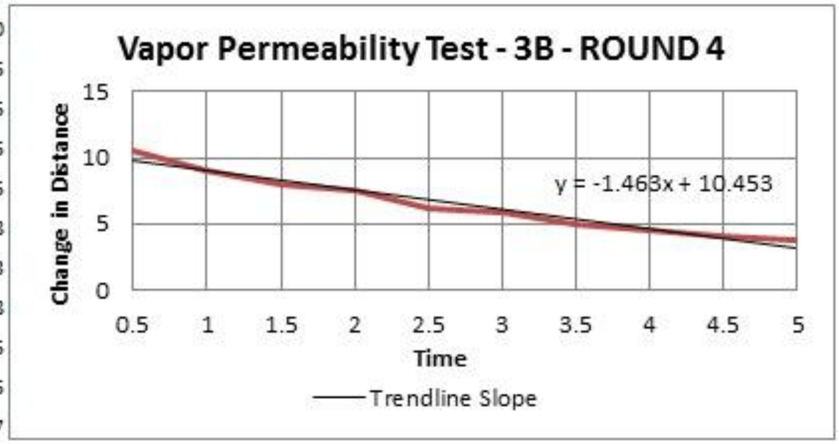
Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
3b	1	0		54
		0.5	25	29
		1	12	17
		1.5	9	8
		2	5.5	2.5
		2.5	9	58
		3	14	44
		3.5	10.5	33.5
		4	9.5	24
		4.5	7	17
		5	6.5	10.5
	2	0		64
		0.5	13	51
		1	10	41
		1.5	9	32
		2	7.5	24.5
		2.5	7	17.5
		3	5.5	12
		3.5	5	7
		4	4	3
		4.5	2	1
		5	1	0
	3	0		70
		0.5	11.5	58.5
		1	11	47.5
		1.5	8	39.5
		2	7.5	32
		2.5	6.7	25.3
		3	5.8	19.5
		3.5	5	14.5
		4	4.5	10
		4.5	4.5	5.5
		5	3.7	1.8



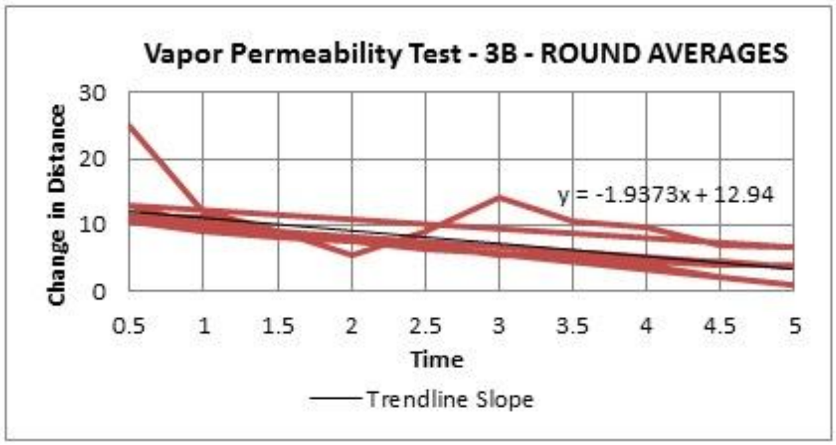




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
3B	4	0		70
		0.5	10.5	59.5
		1	9	50.5
		1.5	8	42.5
		2	7.5	35
		2.5	6.2	28.8
		3	5.8	23
		3.5	5	18
		4	4.5	13.5
		4.5	4	9.5
		5	3.8	5.7

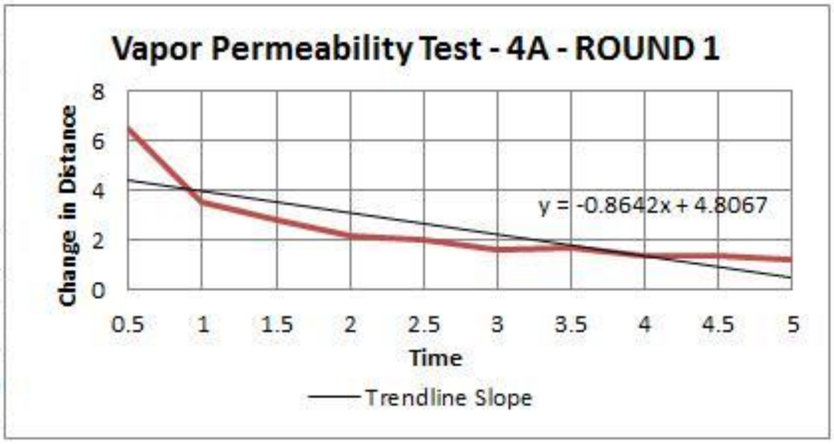


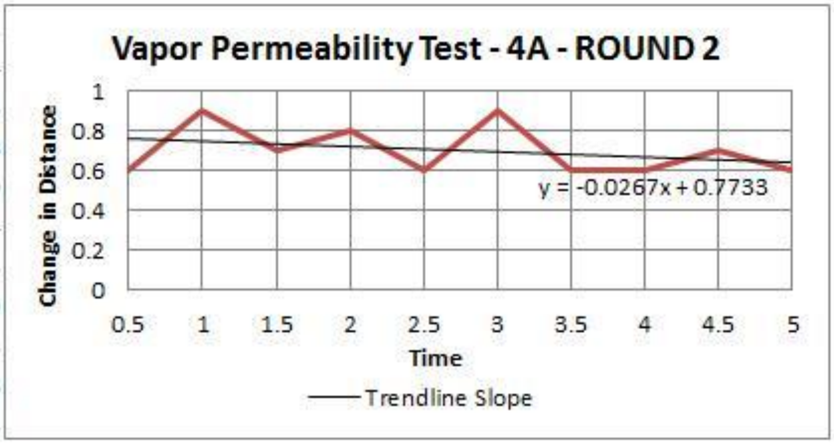
TOTAL Δ D = 304.5

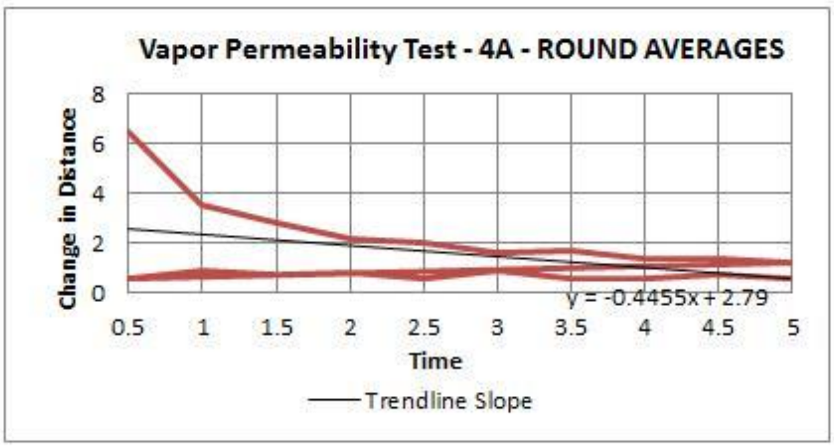


Vapor Permeability Test of 10% Manure-to-Mix Specimen – 4A

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
4A	1	0	0	42
		0.5	6.5	35.5
		1	3.5	32
		1.5	2.8	29.2
		2	2.2	27
		2.5	2	25
		3	1.6	23.4
		3.5	1.7	21.7
		4	1.4	20.3
		4.5	1.4	18.9
		5	1.2	17.7
	2	0	0	42
		0.5	0.6	41.4
		1	0.9	40.5
		1.5	0.7	39.8
		2	0.8	39
		2.5	0.6	38.4
		3	0.9	37.5
		3.5	0.6	36.9
		4	0.6	36.3
		4.5	0.7	35.6
		5	0.6	35
	TOTAL Δ D =		31.3	

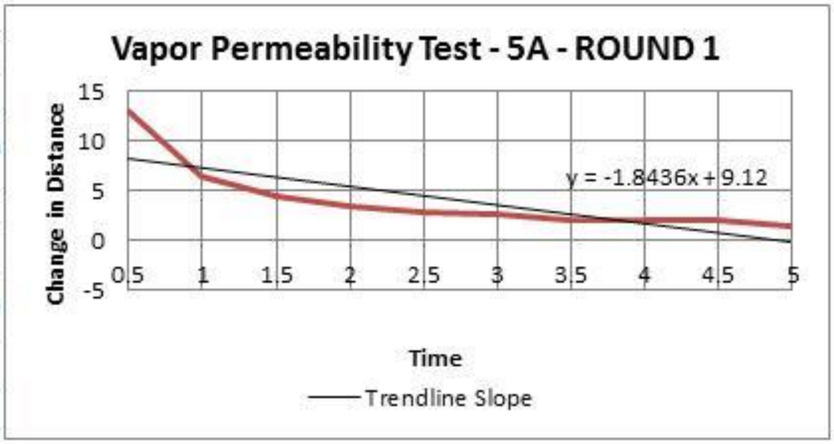


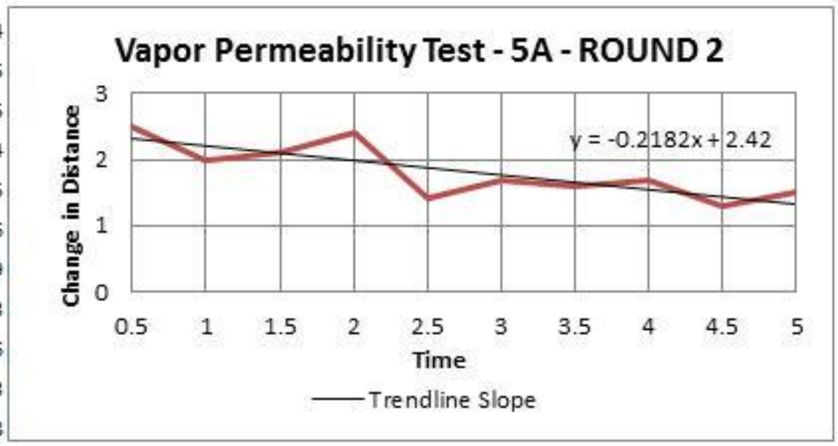


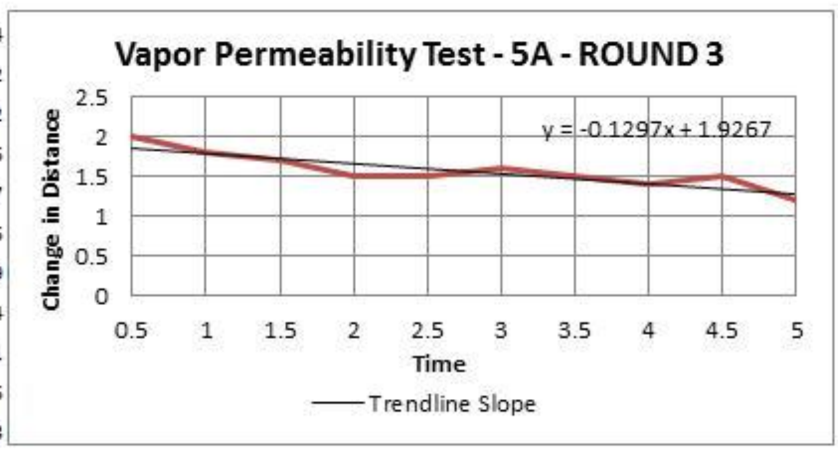


Vapor Permeability Test of 25% Manure-to-Mix Specimen – 5A

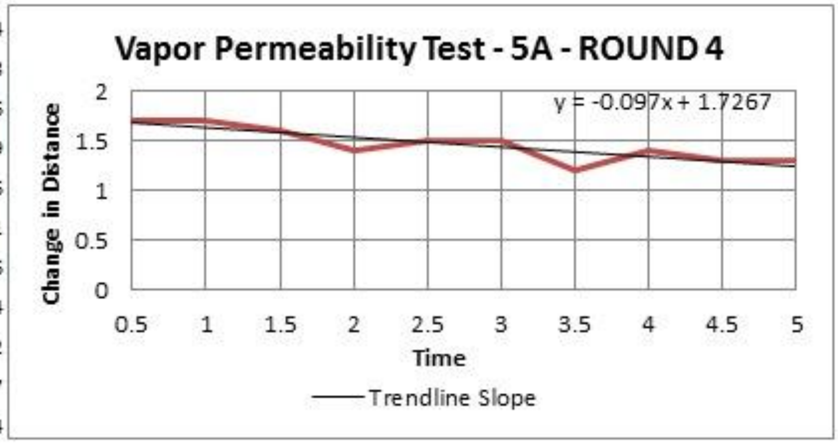
Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
5a	1	0		44
		0.5	13	31
		1	6.5	24.5
		1.5	4.5	20
		2	3.5	16.5
		2.5	2.8	13.7
		3	2.7	11
		3.5	2	9
		4	2	7
		4.5	2	5
		5	1.5	3.5
	2	0		44
		0.5	2.5	41.5
		1	2	39.5
		1.5	2.1	37.4
		2	2.4	35
		2.5	1.4	33.6
		3	1.7	31.9
		3.5	1.6	30.3
		4	1.7	28.6
		4.5	1.3	27.3
		5	1.5	25.8
	3	0		44
		0.5	2	42
		1	1.8	40.2
		1.5	1.7	38.5
		2	1.5	37
		2.5	1.5	35.5
		3	1.6	33.9
		3.5	1.5	32.4
		4	1.4	31
		4.5	1.5	29.5
		5	1.2	28.3

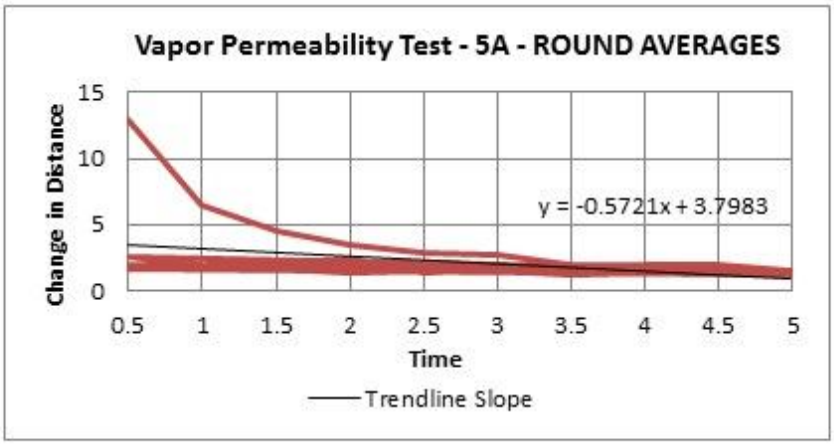






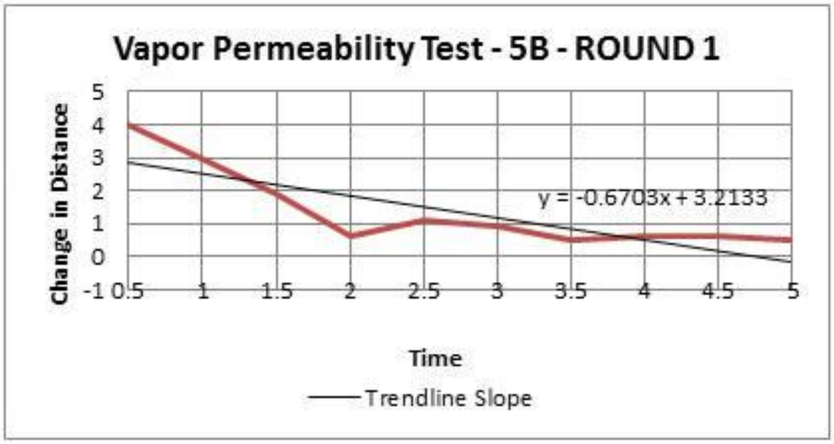
Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
5A	4	0		44
		0.5	1.7	42.3
		1	1.7	40.6
		1.5	1.6	39
		2	1.4	37.6
		2.5	1.5	36.1
		3	1.5	34.6
		3.5	1.2	33.4
		4	1.4	32
		4.5	1.3	30.7
		5	1.3	29.4
		TOTAL Δ D =	89	

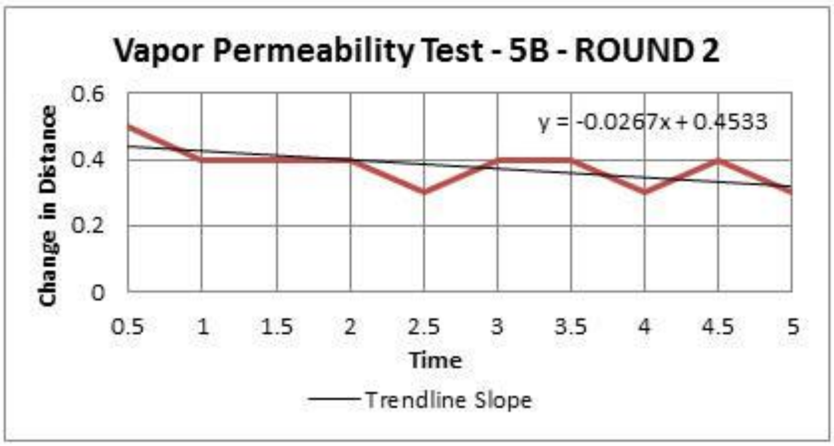


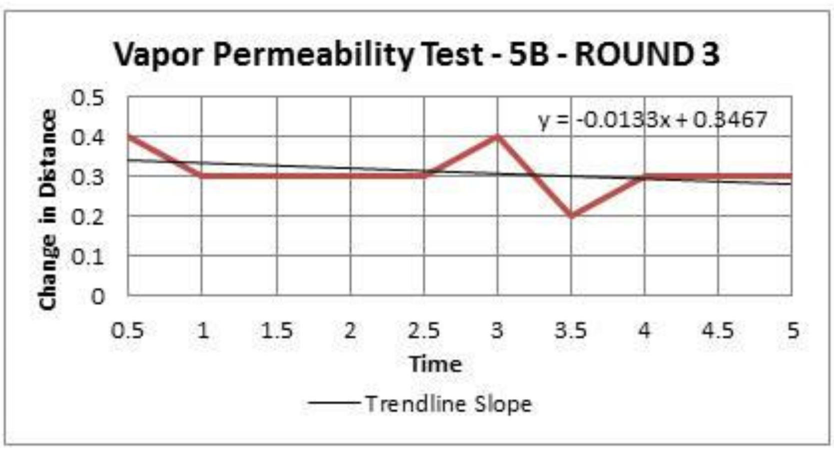


Vapor Permeability Test of 25% Manure-to-Mix Specimen – 5B

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
5b	1	0		48
		0.5	4	44
		1	3	41
		1.5	1.9	39.1
		2	0.6	38.5
		2.5	1.1	37.4
		3	0.9	36.5
		3.5	0.5	36
		4	0.6	35.4
		4.5	0.6	34.8
		5	0.5	34.3
	2	0		33
		0.5	0.5	32.5
		1	0.4	32.1
		1.5	0.4	31.7
		2	0.4	31.3
		2.5	0.3	31
		3	0.4	30.6
		3.5	0.4	30.2
		4	0.3	29.9
		4.5	0.4	29.5
		5	0.3	29.2
	3	0		29
		0.5	0.4	28.6
		1	0.3	28.3
		1.5	0.3	28
		2	0.3	27.7
		2.5	0.3	27.4
		3	0.4	27
		3.5	0.2	26.8
		4	0.3	26.5
		4.5	0.3	26.2
		5	0.3	25.9

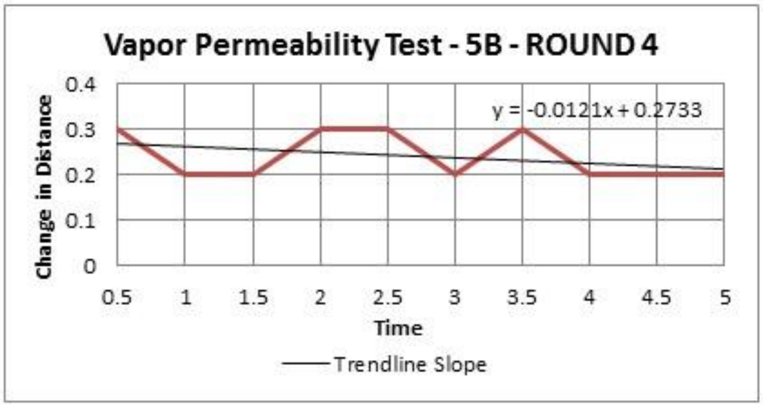


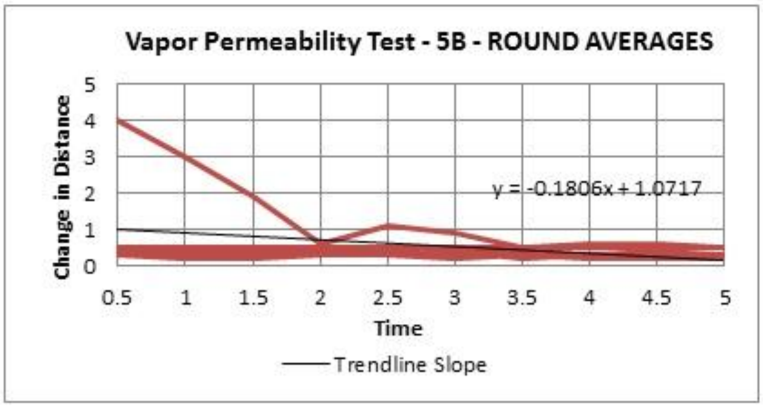




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
5B	4	0		25
		0.5	0.3	24.7
		1	0.2	24.5
		1.5	0.2	24.3
		2	0.3	24
		2.5	0.3	23.7
		3	0.2	23.5
		3.5	0.3	23.2
		4	0.2	23
		4.5	0.2	22.8
		5	0.2	22.6

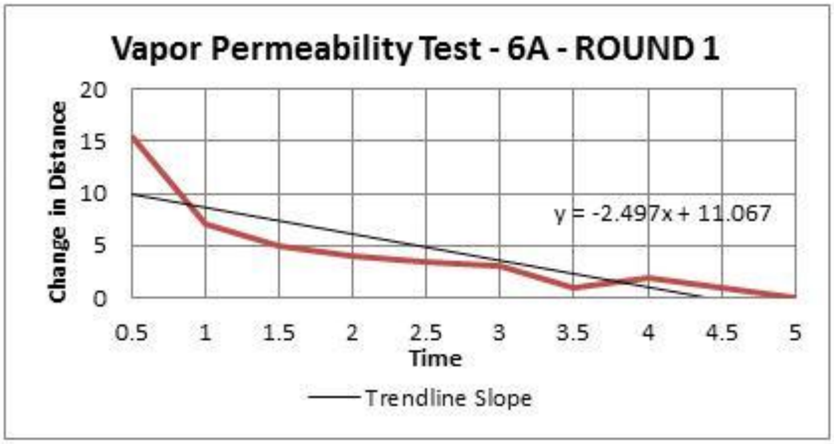
TOTAL Δ D = 23

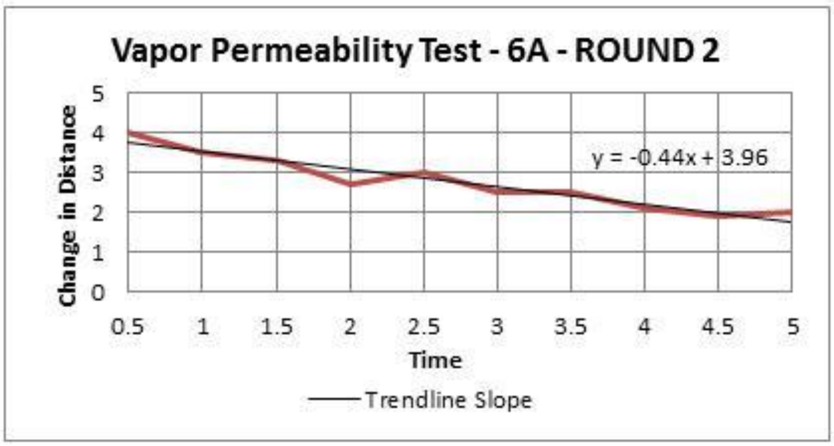


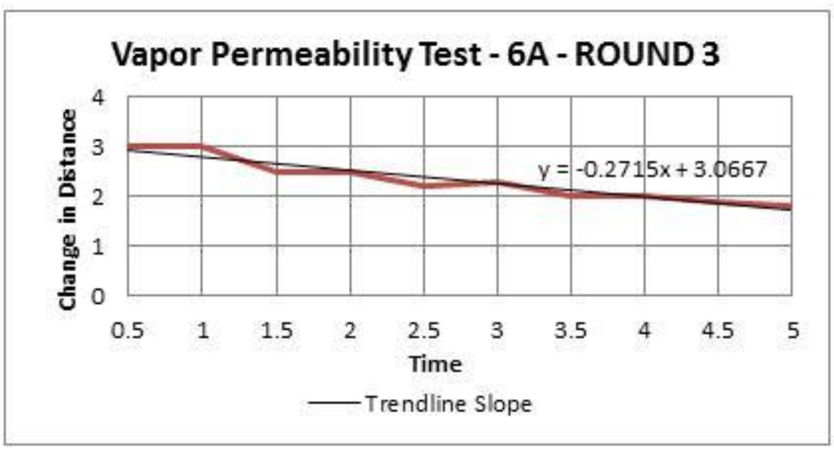


Vapor Permeability Test of 40% Manure-to-Mix Specimen – 6A

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
6a	1	0		42
		0.5	15.5	26.5
		1	7	19.5
		1.5	5	14.5
		2	4	10.5
		2.5	3.5	7
		3	3	4
		3.5	1	3
		4	2	1
		4.5	1	0
		5	0	0
	2	0		41
		0.5	4	37
		1	3.5	33.5
		1.5	3.3	30.2
		2	2.7	27.5
		2.5	3	24.5
		3	2.5	22
		3.5	2.5	19.5
		4	2.1	17.4
		4.5	1.9	15.5
		5	2	13.5
	3	0		41
		0.5	3	38
		1	3	35
		1.5	2.5	32.5
		2	2.5	30
		2.5	2.2	27.8
		3	2.3	25.5
		3.5	2	23.5
		4	2	21.5
		4.5	1.9	19.6
		5	1.8	17.8

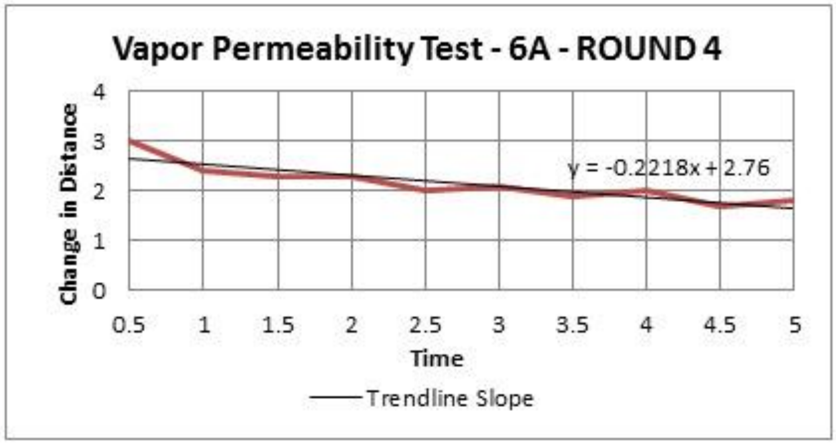


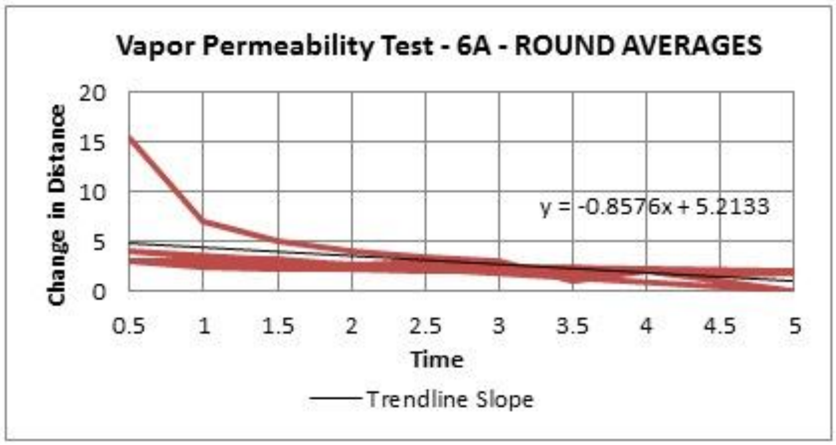




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
6A	4	0		42
		0.5	3	39
		1	2.4	36.6
		1.5	2.3	34.3
		2	2.3	32
		2.5	2	30
		3	2.1	27.9
		3.5	1.9	26
		4	2	24
		4.5	1.7	22.3
		5	1.8	20.5

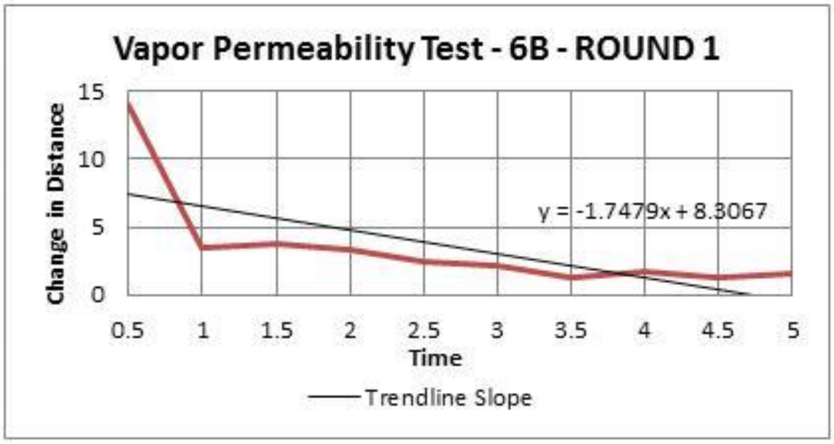
TOTAL Δ D = 114.2

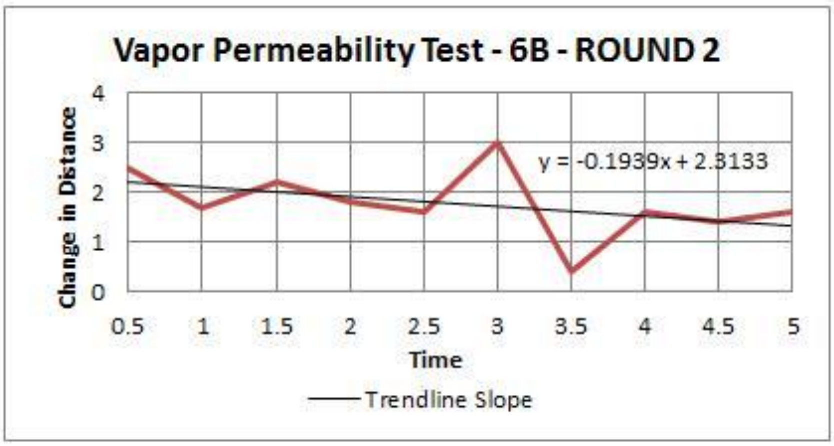


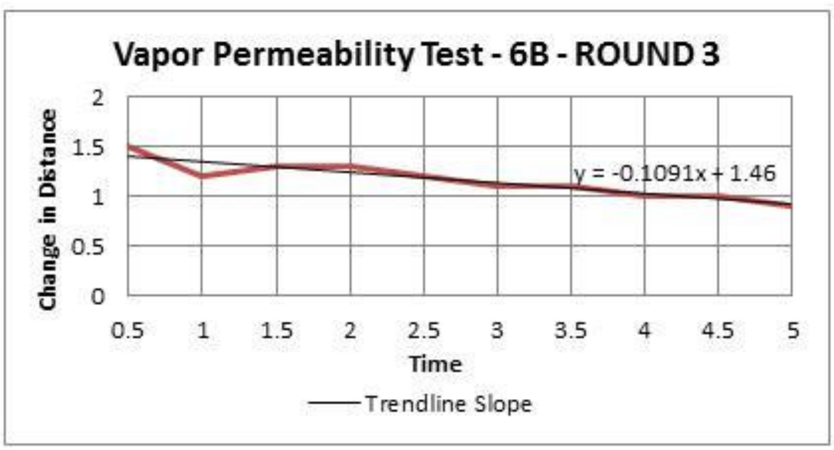


Vapor Permeability Test of 40% Manure-to-Mix Specimen – 6B

Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
6b	1	0		59
		0.5	14	45
		1	3.5	41.5
		1.5	3.7	37.8
		2	3.3	34.5
		2.5	2.5	32
		3	2.2	29.8
		3.5	1.3	28.5
		4	1.7	26.8
		4.5	1.3	25.5
		5	1.5	24
	2	0		69
		0.5	2.5	66.5
		1	1.7	64.8
		1.5	2.2	62.6
		2	1.8	60.8
		2.5	1.6	59.2
		3	3	56.2
		3.5	0.4	55.8
		4	1.6	54.2
		4.5	1.4	52.8
		5	1.6	51.2
	3	0		50
		0.5	1.5	48.5
		1	1.2	47.3
		1.5	1.3	46
		2	1.3	44.7
		2.5	1.2	43.5
		3	1.1	42.4
		3.5	1.1	41.3
		4	1	40.3
		4.5	1	39.3
		5	0.9	38.4

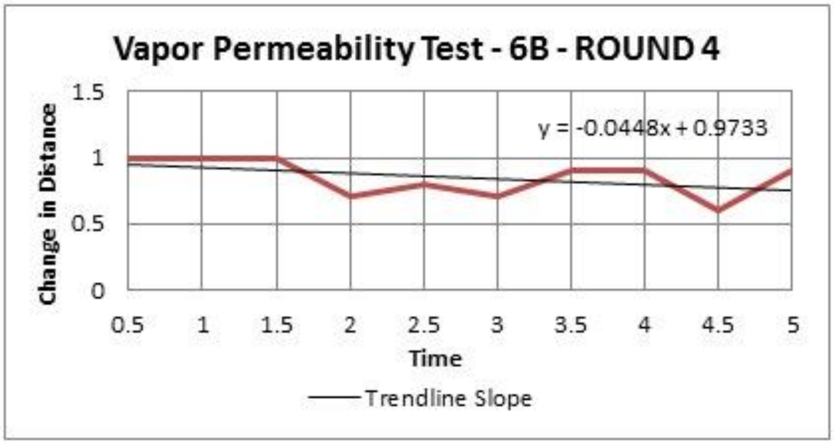


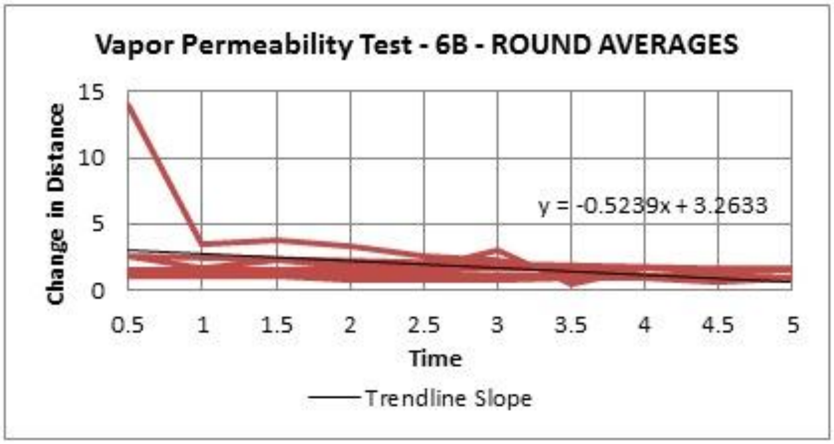




Sample	Round	Time (min)	Δ D (cm)	Dist (cm)
6B	4	0		37
		0.5	1	36
		1	1	35
		1.5	1	34
		2	0.7	33.3
		2.5	0.8	32.5
		3	0.7	31.8
		3.5	0.9	30.9
		4	0.9	30
		4.5	0.6	29.4
		5	0.9	28.5

TOTAL Δ D = 72.9





Appendix I: K-Value Calculations for Vapor Permeability Analysis

K-Values 1/16

To find the coefficient of permeability (K) the following equation was used:

$$K = \frac{aL}{A\,\Delta t} \times \ln\left(\frac{h_1}{h_2}\right)$$

where:

K = coefficient of permeability
a = area of stand pipe
L = Length of sample
A = cross-sectional area of sample
Δt = time during which the change in head is measured
h_1 = water head at beginning of test
h_2 = water head at end of test

(Matt Teto's MQP)

Sample 1a: Earthen Render w/ 10% Lime to Clay

Round 1:

$a = \pi r^2 = \pi(0.5)^2 = 0.79\ in^2$
$L = 3.5''$
$A = \pi r^2 = \pi(3)^2 = 28.27\ in^2$
$\Delta t = 5 - 0 = 5\ min$
$h_1 = 63\ cm \times \frac{1\ in}{2.54\ cm} = 24.80\ in$
$h_2 = 41.8\ cm \times \frac{1\ in}{2.54\ cm} = 16.46\ in$

$$K = \frac{(0.79\ in^2)(3.5\ in)}{(28.27\ in^2)(5\ min)} \times \ln\left(\frac{24.80\ in}{16.46\ in}\right)$$

$$\boxed{K = 0.008018\ in/min}$$

2/16

Round 2:

$a = 0.79\ in^2$
$L = 3.5\ in.$
$A = 28.27\ in^2$
$\Delta t = 5\ min.$
$h_1 = 41\ cm \times \frac{1\ in.}{2.54\ cm} = 16.14\ in.$

$h_2 = 33\ cm \times \frac{1\ in.}{2.54\ cm} = 12.99\ in.$

$$k = \frac{(0.79)(3.5)}{(28.27)(5)} \times \ln\left(\frac{16.14}{12.99}\right)$$

$$\boxed{K = 0.004247\ in/min}$$

Round 3:

$a = 0.79\ in^2$
$L = 3.5\ in.$
$A = 28.27\ in^2$
$\Delta t = 5\ min.$
$h_1 = 32\ cm \times \frac{1\ in.}{2.54\ cm} = 12.60\ in.$

$h_2 = 28.7\ cm \times \frac{1\ in.}{2.54\ cm} = 11.30\ in.$

$$K = \frac{(0.79)(3.5)}{(28.27)(5)} \times \ln\left(\frac{12.60}{11.30}\right)$$

$$\boxed{K = 0.002130\ in/min}$$

3/16

Round 4:

$a = 0.79\ in^2$
$L = 3.5\ in$
$A = 28.27\ in^2$
$\Delta t = 5\ min.$
$h_1 = 28\ cm \times \frac{1\ in.}{2.54\ cm} = 11.02\ in.$

$h_2 = 23.5\ cm \times \frac{1\ in.}{2.54\ cm} = 9.25\ in.$

$$K = \frac{(0.79)(3.5)}{(28.27)(5)} \times \ln\left(\frac{11.02}{9.25}\right)$$

$$\boxed{K = 0.003425\ in./min}$$

$$\text{Average } K = \frac{\Sigma\ \text{K-values from the 4 Rounds}}{4}$$

$$\boxed{\text{Average } K = 0.004455\ in/min}$$

Sample 1b: Earthen Render w/ 10% Lime to Clay

Due to a large void in the sample, the sample could not be tested (it would ruin the instrument). Since Sample 1b had the same dry mix as sample 1a, the K of 1a will be assumed as the K of 1b.

4/16

Sample 2a: Earthen Render w/ 30% Lime to Clay

Round 1:

$a = 0.79 \text{ in}^2$
$L = 3.5''$
$A = 28.27 \text{ in}^2$
$\Delta t = 5 \text{ min.}$

} Same values as sample 1a in all Rounds of 2a.

$h_1 = 64 \text{ cm} \times \frac{1 \text{ in}}{2.54 \text{ cm}} = \underline{25.20 \text{ in.}}$

$h_2 = 21.3 \text{ cm} \times \frac{1 \text{ in}}{2.54 \text{ cm}} = \underline{8.39 \text{ in.}}$

$$K = \frac{(0.79)(3.5)}{(28.27)(5)} \times \ln\left(\frac{25.20}{8.39}\right)$$

$$K = 0.019561 \times \ln\left(\frac{25.20}{8.39}\right)$$

$$\boxed{K = 0.021513 \text{ in/min.}}$$

Round 2:

$a = 0.79 \text{ in}^2$
$L = 3.5''$
$A = 28.27 \text{ in}^2$
$\Delta t = 5 \text{ min.}$

$h_1 = 66 \text{ cm} \times \frac{1 \text{ in}}{2.54 \text{ cm}} = \underline{25.98 \text{ in.}}$

$h_2 = 48 \text{ cm} \times \frac{1 \text{ in}}{2.54 \text{ cm}} = \underline{18.90 \text{ in.}}$

$$K = 0.019561 \times \ln\left(\frac{25.98}{18.90}\right)$$

$$\boxed{K = 0.006224 \text{ in/min}}$$

5/16

Round 3:

$a = 0.79\ in^2$
$L = 3.5''$
$A = 28.27\ in^2$
$\Delta t = 5\ min.$
$h_1 = 47\ cm \times \frac{1\ in.}{2.54\ cm} = 18.50\ in.$

$h_2 = 33.4\ cm \times \frac{1\ in.}{2.54\ cm} = 13.15\ in$

$K = 0.019561 \times \ln\left(\frac{18.50}{13.15}\right)$

$\boxed{K = 0.006677\ in./min.}$

Round 4:

$a, L, A, \Delta t$ = Same as Rounds 1-3 in Sample 2a.

$h_1 = 31\ cm \times \frac{1\ in.}{2.54\ cm} = 12.20\ in.$

$h_2 = 21.5\ cm \times \frac{1\ in.}{2.54\ cm} = 8.46\ in.$

$K = 0.019561 \times \ln\left(\frac{12.20}{8.46}\right)$

$\boxed{K = 0.007161\ in./min.}$

$\boxed{\text{Average } K = 0.010394\ in./min.}$

6/16

Sample 2b:

$a = 0.79\ in^2$
$L = 3.5''$
$A = 25.27\ in^2$
$\Delta t = 5\ min$

For all rounds in this Sample

Round 1:

$h_1 = 41\ cm \times \frac{1\ in}{2.54\ cm} = 16.14\ in.$

$h_2 = 0.5\ cm \times \frac{1\ in}{2.54\ cm} = 0.20\ in.$

$K = 0.019561 \times \ln\left(\frac{16.14}{0.20}\right)$

$\boxed{K = 0.085887\ in./min}$

Round 2:

$h_1 = 41.5\ cm \times \frac{1\ in}{2.54\ cm} = 16.34\ in$

$h_2 = 9.5\ cm \times \frac{1\ in}{2.54\ cm} = 3.74\ in$

$K = 0.019561 \times \ln\left(\frac{16.34}{3.74}\right)$

$\boxed{K = 0.028843\ in./min.}$

Round 3:

$h_1 = 42\ cm \times \frac{1\ in}{2.54\ cm} = 16.54\ in.$

$h_2 = 13.5\ cm \times \frac{1\ in}{2.54\ cm} = 5.31\ in.$

$K = 0.019561 \times \ln\left(\frac{16.54}{5.31}\right) = \boxed{0.022225\ in/min = K}$

7/16

Round 4:

$h_1 = 41\,cm \times \frac{1\,in.}{2.54\,cm} = 16.14\,in.$

$h_2 = 15\,cm \times \frac{1\,in.}{2.54\,cm} = 5.91\,in.$

$K = 0.019561 \times \ln\left(\frac{16.14}{5.91}\right)$

$\boxed{K = 0.019652\ in./min.}$

$\boxed{\text{Average } K = 0.039152\ in./min.}$

Sample 3a:

$a = 0.79\,in^2$
$L = 3.5''$
$A = 28.27\,in^2$
} same for all round

Round 1: K will be calculated twice b/c the water needed to be added twice.

$\Delta t = 2 - 0 = 2\,min$

$h_1 = 50\,cm \times \frac{1\,in}{2.54\,cm} = 19.69\,in.$

$h_2 = 3\,cm \times \frac{1\,in}{2.54\,cm} = 1.18\,in.$

$K = \frac{(0.79)(3.5)}{(28.27)(2)} \times \ln\left(\frac{19.69}{1.18}\right)$

$\boxed{K = 0.187643\ in./min.}$

8/16

$\Delta t = 5 - 2.5 = 2.5$ min.

$h_1 = 58.9 \text{ cm} \times \frac{1 \text{ in.}}{2.54 \text{ cm}} = 23.19 \text{ in.}$

$h_2 = 13.8 \text{ cm} \times \frac{1 \text{ in.}}{2.54 \text{ cm}} = 5.43 \text{ in.}$

$$K = \frac{(0.79)(3.5)}{(28.27)(2.5)} \times \ln\left(\frac{23.19}{5.43}\right)$$

$$\boxed{K = 0.056796 \text{ in./min}}$$

Round 2:

$\Delta t = 5$ min.

$h_1 = 61.5 \text{ cm} \times \frac{1 \text{ in.}}{2.54 \text{ cm}} = 24.21 \text{ in.}$

$h_2 = 2.5 \text{ cm} \times \frac{1 \text{ in.}}{2.54 \text{ cm}} = 0.98 \text{ in.}$

$$K = 0.019561 \times \ln\left(\frac{24.21}{0.98}\right)$$

$$\boxed{K = 0.062732 \text{ in./min}}$$

Round 3:

$\Delta t = 5$ min.

$h_1 = 64 \text{ cm} \times \frac{1 \text{ in.}}{2.54 \text{ cm}} = 25.20 \text{ in.}$

$h_2 = 13.5 \text{ cm} \times \frac{1 \text{ in.}}{2.54 \text{ cm}} = 5.31 \text{ in.}$

$$K = 0.019561 \times \ln\left(\frac{25.20}{5.31}\right) = \boxed{0.030461 \text{ in./min} = K}$$

9/16

Round 4:

$\Delta t = 5$ min.

$h_1 = 65\,cm \times \frac{1\,in.}{2.54\,cm} = 25.59$ in.

$h_2 = 20.8\,cm \times \frac{1\,in.}{2.54\,cm} = 8.19$ in.

$K = 0.019561 \times \ln\left(\frac{25.59}{8.19}\right)$

$\boxed{K = 0.022286 \text{ in./min.}}$

$\boxed{\text{Averag } K = 0.061984 \text{ in/min.}}$

Sample 3b:

$a = 0.79\,in^2$
$L = 3.5''$
$A = 28.27\,in^2$
} For all Rounds of Sample 3b.

Round 1: K is calculate twice b/c water was added twice.

$\Delta t = 2 - 0 = 2$ min
$h_1 = 54\,cm = 21.26$ in.
$h_2 = 2.5\,cm = 0.98$ in.

$K = \frac{(0.79)(3.5)}{(28.27)(2)} \times \ln\left(\frac{21.26}{0.98}\right) = \boxed{0.150477 \text{ in./min} = K}$

$\Delta t = 5 - 2.5\,min = 2.5$ min.
$h_1 = 58\,cm = 22.83$ in.
$h_2 = 10.5\,cm = 4.13$ in.

$K = \frac{(0.79)(3.5)}{(28.27)(2.5)} \times \ln\left(\frac{22.83}{4.13}\right) = \boxed{0.066892 \text{ in/min} = K}$

10/16

Round 2:

$\Delta t = 4.5$ min.

$h_1 = 64$ cm $= 25.20$ in.
$h_2 = 1$ cm $= 0.39$ in.

$$K = \frac{(0.79)(3.5)}{(28.27)(4.5)} \times \ln\left(\frac{25.20}{0.39}\right) = \boxed{0.090601 \text{ in/min} = K}$$

Round 3:

$\Delta t = 5$ min.
$h_1 = 70$ cm $= 27.56$ in.
$h_2 = 1.8$ cm $= 0.71$ in.

$$K = 0.019561 \times \ln\left(\frac{27.56}{0.71}\right) = \boxed{0.071571 \text{ in/min} = K}$$

Round 4:

$\Delta t = 5$ min.
$h_1 = 70$ cm $= 27.56$ in.
$h_2 = 5.7$ cm $= 2.24$ in.

$$K = 0.019561 \times \ln\left(\frac{27.56}{2.24}\right) = \boxed{0.049096 \text{ in/min} = K}$$

$\boxed{\text{Average } K = 0.085727 \text{ in/min}}$

Sample 4a:

$$\left.\begin{array}{l} a = 0.79 \text{ in}^2 \\ L = 3.5 \text{ in.} \\ A = 28.27 \text{ in}^2 \\ \Delta t = 5 \text{ min.} \end{array}\right\} \text{For all Rounds}$$

11/16

Round 1:

$h_1 = 42$ cm $= 16.54$ in.
$h_2 = 17.7$ cm $= 6.97$ in.

$K = 0.019561 \times \ln\left(\frac{16.54}{6.97}\right) = \boxed{0.016904 \text{ in./min.} = K}$

Round 2:

$h_1 = 42$ cm $= 16.54$ in.
$h_2 = 35$ cm $= 13.78$ in.

$K = 0.019561 \times \ln\left(\frac{16.54}{13.78}\right) = \boxed{0.003571 \text{ in/min} = K}$

$\boxed{\text{Average K} = 0.010238 \text{ in/min}}$

Sample 4b:

Sample 4b could not be tested b/c it had a large void.

Sample 5a:

$a = 0.79 \text{ in}^2$
$L = 3.5$ in.
$A = 28.27 \text{ in}^2$
$\Delta t = 5$ min.

Same for all rounds

Round 1:

$h_1 = 44$ cm $= 17.32$ in.
$h_2 = 3.5$ cm $= 1.38$ in.

$K = 0.019561 \times \ln\left(\frac{17.32}{1.38}\right) = \boxed{0.049485 \text{ in./min} = K}$

12/16

Round 2:

$h_1 = 44\ cm = 17.32\ in$
$h_2 = 25.8\ cm = 10.16\ in.$

$$K = 0.01956l \times \ln\left(\frac{17.32}{10.16}\right) = \boxed{0.010434\ in/min = K}$$

Round 3:

$h_1 = 44\ cm = 17.32\ in.$
$h_2 = 28.3\ cm = 11.14\ in.$

$$K = 0.019561 \times \ln\left(\frac{17.32}{11.14}\right) = \boxed{0.008633\ in/min = K}$$

Round 4:

$h_1 = 44\ cm = 17.32\ in.$
$h_2 = 29.4\ cm = 11.57\ in.$

$$K = 0.019561 \times \ln\left(\frac{17.32}{11.57}\right) = \boxed{0.007892\ in/min = K}$$

$\boxed{\text{Average } K = 0.01911\ in./min}$

Sample 5b:

$$\left.\begin{array}{l} a = 0.79\ in^2 \\ L = 3.5\ in \\ A = 28.27\ in^2 \\ \Delta t = 5\ min \end{array}\right\} \text{Same for all rounds}$$

Round 1:

$h_1 = 48\ cm = 18.90\ in$
$h_2 = 34.3\ cm = 13.50\ in$

$$K = 0.019561 \times \ln\left(\frac{18.90}{13.50}\right) = \boxed{0.006582\ in/min = K}$$

12/16

Round 2:

$h_1 = 44\ cm = 17.32\ in$
$h_2 = 25.8\ cm = 10.16\ in.$

$$K = 0.019561 \times \ln\left(\frac{17.32}{10.16}\right) = \boxed{0.010434\ in/min = K}$$

Round 3:

$h_1 = 44\ cm = 17.32\ in.$
$h_2 = 28.3\ cm = 11.14\ in.$

$$K = 0.019561 \times \ln\left(\frac{17.32}{11.14}\right) = \boxed{0.008633\ in/min = K}$$

Round 4:

$h_1 = 44\ cm = 17.32\ in.$
$h_2 = 29.4\ cm = 11.57\ in.$

$$K = 0.019561 \times \ln\left(\frac{17.32}{11.57}\right) = \boxed{0.007892\ in/min = K}$$

$$\boxed{\text{Average } K = 0.01911\ in./min}$$

Sample 5b:

$$\left.\begin{array}{l} a = 0.79\ in^2 \\ L = 3.5\ in \\ A = 28.27\ in^2 \\ \Delta t = 5\ min \end{array}\right\} \text{Same for all rounds}$$

Round 1:

$h_1 = 48\ cm = 18.90\ in$
$h_2 = 34.3\ cm = 13.50\ in$

$$K = 0.019561 \times \ln\left(\frac{18.90}{13.50}\right) = \boxed{0.006582\ in/min = K}$$

14/16

Round 2:

$\Delta t = 5$ min
$h_1 = 41$ cm $= 16.14$ in.
$h_2 = 13.5$ cm $= 5.31$ in.

$K = 0.019561 \times \ln\left(\frac{16.14}{5.31}\right) = \boxed{0.021746 \text{ in/min.} = K}$

Round 3:

$\Delta t = 5$ min
$h_1 = 41$ cm $= 16.14$ in.
$h_2 = 17.8$ cm $= 7.01$ in.

$K = 0.019561 \times \ln\left(\frac{16.14}{7.01}\right) = \boxed{0.016313 \text{ in/min.} = K}$

Round 4:

$\Delta t = 5$ min.
$h_1 = 42$ cm $= 16.54$ in.
$h_2 = 20.5$ cm $= 8.07$ in.

$K = 0.019561 \times \ln\left(\frac{16.54}{8.07}\right) = \boxed{0.014038 \text{ in/min} = K}$

$\boxed{\text{Average } K = 0.035932 \text{ in/min}}$

Sample 6b:

$a = 0.79$ in^2
$L = 3.5$ in
$A = 28.27$ in^2
$\Delta t = 5$ min.

} Same for all rounds

Round 1:

$h_1 = 59$ cm $= 23.23$ in.
$h_2 = 24$ cm $= 9.45$ in.

$K = 0.019561 \times \ln\left(\frac{23.23}{9.45}\right) = \boxed{0.017594 \text{ in/min} = K}$

15/16

Round 2:

$h_1 = 69\text{ cm} = 27.17\text{ in.}$
$h_2 = 51.2\text{ cm} = 20.16\text{ in.}$

$$K = 0.019561 \times \ln\left(\frac{27.17}{20.16}\right) = \boxed{0.005837\text{ in/min} = K}$$

Round 3:

$h_1 = 50\text{ cm} = 19.69\text{ in.}$
$h_2 = 38.4\text{ cm} = 15.12\text{ in.}$

$$K = 0.019561 \times \ln\left(\frac{19.69}{15.12}\right) = \boxed{0.005166\text{ in/min} = K}$$

Round 4:

$h_1 = 37\text{ cm} = 14.57\text{ in.}$
$h_2 = 28.5\text{ cm} = 11.22\text{ in.}$

$$K = 0.019561 \times \ln\left(\frac{14.57}{11.22}\right) = \boxed{0.005111\text{ in/min} = K}$$

$$\boxed{\text{Average } K = 0.008427\text{ in/min}}$$

Sample C1:

Sample C1 could not be tested due to large voids.

Sample C2:

$a = 0.79\text{ in}^2$
$L = 3.5\text{ in.}$
$A = 28.27\text{ in}^2$
$\Delta t = 5\text{ min.}$

Same for all rounds.

16/16

Round 1:

$h_1 = 41\,cm = 16.14\,in.$
$h_2 = 28\,cm = 11.02\,in.$

$$K = 0.019561 \times \ln\left(\frac{16.14}{11.02}\right) = \boxed{0.0074464\ in/min = K}$$

Round 2:

$h_1 = 42\,cm = 16.54\,in.$
$h_2 = 35.4\,cm = 13.94\,in.$

$$K = 0.019561 \times \ln\left(\frac{16.54}{13.94}\right) = \boxed{0.003345\ in/min = K}$$

Round 3:

$h_1 = 42.5\,cm = 16.73\,in.$
$h_2 = 40.4\,cm = 15.91\,in.$

$$K = 0.019561 \times \ln\left(\frac{16.73}{15.91}\right) = \boxed{9.83 \times 10^{-4}\ in/min. = K}$$

Round 4:

$h_1 = 40.4\,cm = 15.91\,in.$
$h_2 = 38.9\,cm = 15.31\,in.$

$$K = 0.019561 \times \ln\left(\frac{15.91}{15.31}\right) = \boxed{7.52 \times 10^{-4}\ in/min = K}$$

$\boxed{\text{Average } K = 0.003136\ in/min.}$

Appendix J: Project Proposal

Worcester Polytechnic Institute

Straw Bale Construction: The Application In Massachusetts

Major Qualifying Project

Magwood, C., & Walker, C. (2001)

Hajar Jafferji, Karina Raczka, Yao Wang
12/17/2010

Abstract

Current sustainable design and construction efforts can make energy efficient homes up to 90% less energy intensive than standard structures that are built to the same building code (Zeller Jr., 2010). One method of building energy efficient structures is through straw bale construction. Building with straw bales has several remarkable advantages that conventional materials, such as wood, steel and concrete, lack in terms of cost, abundance, and sustainability. However, the most distinct advantage of straw bale is that it is a highly efficient thermal insulator. Straw bale construction is utilized around the world and in the United States, but is not widely developed in Massachusetts. The goal of this project is to determine the applicability of straw bale construction in Massachusetts. Factors such as structural strength, thermal capacity, vapor permeability and cost will be evaluated through research and testing procedures. In addition, a straw bale house will be designed for Worcester, MA by following the Commonwealth of Massachusetts State Building Code. Through the findings of this project, it will be determined if straw bale construction can be an alternative to standard construction methods in Massachusetts.

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Chapter 1: Introduction

Now more than ever, sustainable construction efforts are being made to mitigate the amount of energy that is used behind the procurement and transportation of construction resources and materials. Currently, 45% of all the energy consumed in the world is used in the manufacturing and transportation of building and construction materials (Earth Garden, 2004). In addition, most standing structures are not in the least bit energy efficient. In the United States alone, as much as 70% of the electricity consumed and 40% of carbon dioxide emitted by residential homes is wasted due to the fact that many structures are poorly insulated and need excessive amounts of electricity and fuel to make up for it (Zeller Jr., 2010).

Energy and resource conservation has become a popular priority in today's construction industry. Whether it is to save energy costs or to genuinely act more sustainably, both commercial and private interest groups have been growing more concerned on making buildings more "green". Green characteristics include efficient energy usage, water efficacy, decreased carbon dioxide emissions, and improvements in indoor air qualities (U.S. Green Building Council, 2010).

Current sustainable design and construction efforts can make energy efficient homes up to 90% less energy intensive than standard structures that are built to the same building code (Zeller Jr., 2010). One method of building energy efficient structures is through straw bale construction.. Building with straw bales has several remarkable advantages that building with conventional materials such as wood, steel and concrete lack in terms of cost, abundance, and sustainability. However, the most distinct advantage of straw bale is that it is a highly efficient thermal insulator.

Although straw bale houses have been built in many areas around the world as well as in the United States, straw bale construction has not been readily utilized in Massachusetts. The goal of this project is to determine the applicability of straw bale as a construction material in Massachusetts by evaluating the various aspects of straw bale construction. Factors such as structural strength, thermal capacity, vapor permeability and cost will be evaluated.

Chapter 2: Background

Straw is remarkably strong as it has a similar molecular structure to that of wood. When densely baled together, straw accounts for numerous qualities that are very favorable for construction. A common misconception concerning straw is that it should not be used for construction as most people initially imagine straw to be a loose and unsteady stuffing material. As this is true for individual grains of straw, baled straw is actually a very effective construction material because of its high density. To clarify, the distinction between straw and straw bales can be compared to sheets of paper and a heavy bounded book. As sheets of paper are very weak and unstable individually, they work in the contrary when bounded together. Another misconception concerning straw bale is that it is hazardous in terms of combustion. However, because straw bales are densely compacted, they are actually very fire resistant as there is limited oxygen within the bale to permit combustion.

Building with straw bales has several advantages that building with conventional materials such as wood, steel and concrete lack, especially for energy efficient structures. The most distinct advantage is the high R-value of straw bales that make buildings thermally efficient and energy conserving. R-value is a number that signifies the thermal resistance of an insulator. Researches to date report the R-value of bales ranging from 5.2 to 10.8 per inch, which is significantly higher than that of wood (1.0 per inch), brick (0.2 per inch) and fiberglass batts (3.0 per inch) (Stone, 2003).

In addition to being environmentally friendly, straw bale construction is also considered sustainable and economical because straw is so renewable and abundant. In contrast to many construction materials, straw can be grown in less than six months and does not call for an exorbitant amount of energy to produce. For example, it costs 6.15 million kJ of energy to manufacture one ton of concrete where it only costs 119,250 kJ of energy to produce one ton of straw (Earth, 2006). In addition, it is needless to mention that one ton of straw can also be used more sparingly than one ton of cement could.

2.2. Construction Methods

When building with straw bales, two fundamental types of construction methods can be applied: the load bearing method, and the infill method.

The load bearing method entails for the straw bale walls to support all the loads that a structure encounters (e.g. roof, floors, snow, etc.). Under this method, walls are generally created by stacking bales of straw together so that there are no gaps or spaces in between them, and corners are interlocked so that they join together. Advantages in this method include ease of construction and significantly reducing the need of other building materials (e.g. wood, concrete) (Steen & Bainbridge, 1994).

One major disadvantage concerning the load bearing method is how limited the size of a structure can be. The larger a load bearing straw bale structure is, the more difficult it becomes for the structure to stand and resist the loads that are acting upon it. Another negative aspect includes the fact that straw is more prone to settle under this method and thus may require frequent maintenance (Steen & Bainbridge, 1994).

Straw bale can also be utilized as an infill material within a structural frame of another material (e.g.. wood, steel, reinforced concrete) so that it plays the role as an insulator instead of the primary -load bearing material. A very important aspect to building an infill structure is how the frame is placed alongside the straw bale. Depending on what the structure is going to be used for, it may help to determine the type of frame layout that is to be used. For instance, a framework that is placed outside a bale wall allows for more creative design as straw bales can be shaped in various ways. In this case, two different footings of foundations would be needed: one for the posts and one for the straw bales (Mack & Therrien, 2005).Generally speaking, there are no limitations when it comes to using straw bale as an infill material, as long as the foundation is appropriately designed and the render is appropriately applied to deter weather and allow for vapor transmission.

Framework that is located within load bearing straw bale walls is another option known as the hybrid method. The advantage to this method is that only one foundation needs to be set. However, the main drawback is that thermal bridging may occur in which heat passes through a certain pathway at a faster speed than the area around it (Jones, 2001). Thus, materials that have minimal insulation qualities, such as steel and concrete, are required to be spaced certain distances apart from the straw bales.

2.3. Interior (Render) and Exterior (Render) Finishes

As straw bales are most vulnerable to rainwater, the main purpose of finishing a straw bale wall is to protect the bales from water intrusion. Even though rain poses as the most imminent threat to straw bale, choosing an appropriate render is a critical aspect in straw bale construction because different finishes will react differently to various weather conditions. For example, an earth render is not the best choice on a site that receives a lot of horizontal weather. Cement stucco might not be either, unless the climate also provides substantial drying periods. Lime renders are more versatile to weather conditions yet are prone to be maintained more frequently. Plaster and render finishes can include lime, cement, gypsum, clay and earth materials (Lacinski & Bergeron, 2000).

There are a few factors that attribute to choosing a plaster and render finish. One factor is preference. Clay and lime finishes are favored over cement stucco due to their ease of application, aesthetic appeal and are also believed to cause fewer problems that pertain to moisture. Alternative finishes can include siding and paneling for wet and windy locations (Lacinski & Bergeron, 2000).

A second factor includes whether or not a finish should supply any structural support. Larger load bearing structures, buildings in seismically active zones or in heavy snow-load regions may require wire-reinforced cement stucco for additional structural stability. Reinforced cement stucco can also be rendered for infill buildings to resist shear loads. Even though lime and clay finishes have not been widely tested in certain high-load environments, it is possible that these materials are capable of resisting structural loads

(Lacinski & Bergeron, 2000). This general uncertainty will be one area of research to be explored in this project.

A third factor attributes to the breathability of the rendered bale walls. It is very essential that straw bale walls can "breathe", that is, to have the ability of diffusing water vapor as well as other gases through the wall. The efficiency of a finish is deemed on how well it allows the covered bale to breathe or dry (Steen & Bainbridge, 1994).

Amongst all the types of finishes, three popular choices among straw bale constructions are lime, cement stucco and earth based.

Lime

When applied appropriately, lime is a very pragmatic finish as it is a flexible material and makes the straw bale structure breathable. Lime has been used to bind stone and brick as a building finish for thousands of years. However, as the preparation and practice of lime work is straightforward, the variables in rendering the material are crucial to the overall durability of the material (Jones, 2001). Various combinations of lime, cement, sand, and water can provide different effects in lime rendering. Based on the finished consistency, weather conditions during application, method of application, and other conditions of application, rendering durations can last anytime between a few days to months (Earth Garden, 2004).

Cement

Even though cement is waterproof and works as an exceptional impermeable surface in an ideal state, faltered cement rendered straw bale structures are vulnerable to leaks and dampness. Due to the rigidity of cement, it is almost impossible not to have cracks after a short period of time, especially when applied to a flexible backing material like straw. If rain passes through cracks, water will filter down and collect at the bottom of the wall where it cannot escape. In other words, cracks in cement renders can result in a buildup of trapped moisture that will inevitably cause rotting (Jones, 2001).

Cement finishes are also difficult to work with, embody a copious amount of energy, and can make structures in wet climates look begrimed not too long after rendering. Even though cement stucco, especially when reinforced by wire, increases a bale's ability to resist both compressive and shear loads, which adds rigidity in dry climates when a structural element is needed, there are more disadvantages to using cement as a straw bale finish as opposed to other renders (Lacinski & Bergeron, 2000).

Clay and Earth

Clay types differ but generally consist of about 20% clay to 80% sand for both renders and renders and are very durable. However, clay finishes are usually used as plasters unless a clay render was accompanied with a lime finish (Jones, 2001). Clay and earth renders allow breathability, are compatible with lime, easy to work with, nontoxic, reusable, usually inexpensive, and even absorb sound well. The only energy involved in manufacturing clay finish is spent in digging, transportation and in some cases, milling (Lacinski & Bergeron, 2000)

In this project, we will determine what type of finish will be ideal for New England in terms of structural integrity and breathability in regards to weather and loading conditions.

2. 4. Relationship with Other Construction Elements

As bales are usually used to support interior and exterior walls, such wall systems must also accommodate other construction elements such as foundations, floors and roofs.

Practically, all kinds of code-approved foundations, floors and roofs can be used for straw bale construction. However, special attention should be paid when bale walls are attached to other construction elements. For example, foundations should be high enough to protect the bottom of the wall from moisture. Attention should be made to the method of connection between the foundation and the first course of bales; Roof structures are often influenced by the type of bale-wall construction, as the roof and the roof plate contribute significantly to the final stability of the load bearing structure. Thus the load bearing structure allows less flexibility with roof types while the infill structure can accommodate almost all popular roof structures. (Steen & Bainbridge, 1994).

2.5. Structural Analysis of Straw Bale Construction

With all the aspects to be considered when building with straw bale, the principle factor to regard for during construction is the structural behavior of the material, especially for load bearing structures that incorporate various loading conditions.

As is the case in most bale wall systems, when renders are applied to the surfaces of bale walls, a hybrid system of straw and render structure is established. Effectively, any further loading forces, such as snow, wind, earthquakes, dead, live, etc., will mostly or entirely be distributed into the render coatings. This is because of the relative stiffness, or the relative modules of elasticity, of the two disparate materials. As most of render types are far stiffer than the straw bales, they will therefore “attract” any subsequent loading (King, 2005).

Though it is essential to regard the render coatings as the primary load-carrying elements, it is nevertheless also important to recognize that the straw bales are still crucial elements of the structure. The adhesiveness between the render and bales transfers any loads acting upon the bales to the render coatings and further onto the foundation. This is the fundamental theory behind any load bearing structure designs (King, 2005).

In this project, the structural performances of rendered bales and the adhesiveness between render and straw bales will be analyzed.

2.6. Commonwealth of Massachusetts State Building Code (CMR)

Straw bale buildings can encounter the same problems with building codes as many other ecologically sound, proven methods of construction. It is necessary to for anyone who is to work with straw bale to investigate the state building code and analyze all aspects of the straw bale construction within the context of the code.

The current applicable state building code is the Seventh Edition of Commonwealth of Massachusetts State Building Code (780 CMR) that is based on the ICC International Building Code 2003 with significant Massachusetts modifications. (Commonwealth of Massachusetts, 2008)CMR consists of two volumes; one addressing all building uses except one- and two-family dwellings and the other addressing only one- and two-family dwellings. Since most straw bale constructions in practice are private family houses (Steen & Bainbridge, 1994), the group decided to conduct primary investigation on such type of construction, and thus will utilize the second volume of CMR, for one- and two-family dwellings.

CMR lists all aspects of family house constructions, including design loads, layout planning, approved types of materials, approved types of foundations, floors, walls and roofs, energy efficiency, etc. The use of alternative materials, appliances, equipment or methods of design or construction shall be approved when the said alternative is satisfactory and complies with the intent of the provisions of CMR approved materials and methods of construction in quality, strength, effectiveness, fire resistance, durability, and safety (Commonwealth of Massachusetts, 2008),

In the case of straw bale, the primary concerns lie in the design and construction of structures, especially interior and exterior wall systems. As discussed in the previous sections, straw bales are primarily used for wall systems in building construction, either serving for load-bearing, or in-fill. Therefore, the scope of this project will focus on the structural analysis of straw bale walls in the context of CMR.

Additionally, since thermal resistance is the most distinct benefit of straw bale construction, the energy efficiency aspect of the material in the context of the Energy section of CMR will also be evaluated.

Chapter 3: Scope of Work

Throughout the course of this project in discussing the significant impacts of straw bale usage, the process as outlined below in Table 1 will consist of the following research areas: literature reviews, test preparation, laboratory testing, result analysis, and designing a working plan for Worcester, MA. With respects to research development, existing straw bale data through literature review, interviews of professionals with first-person experience, literature review of building codes with respect to straw bale, and case studies of supporting data will be gathered for analysis.

Before the testing of materials commences, the testing sample recipes will be determined, standardized, and implemented throughout the laboratory testing. Once the straw bale and rendering materials are acquired, they will be prepared according to the predetermined recipes and ASTM standards. After the first set of straw bale materials has been rendered and the specimens have dried, the testing process will begin.

During the laboratory testing, data will be gathered for analysis. All data gathered will be utilized in creating a design for a one-family, straw bale structure in Worcester, MA. With completion of the design structure, the final conclusion will discuss the ramification of such developments and how they would impact future developments in Massachusetts.

Table 1: Tentative Schedule for Tasks

Week	1(A)	2	3	4	5	6	7	8	9 (B)	10	11	12	13	14	15	16
Date	8/30						10/11	10/18	10/25	11/1	11/8	11/15	11/22	11/29	12/6	12/13
Research	Literature Review						Contacting Local Straw Bale Professionals		Literature Review of Building Codes and Existing Straw Bale		Case Studies of Available Tests Done to Date					
Test Prep						Determination of Testing Samples and Recipes	Acquiring Rendering Materials and Straw Bales		Preparation of Testing Specimens (Mixing and Rendering)	Curing Specimens						
Lab Tests												Various Tests				
Results Analysis														Results Analysis		
Design									Design a One-family Straw Bale Structure in Worcester, MA							
Conclusion															Conclusion	
Report						Proposal					Final Report					

Chapter 4: Methodology

This chapter extensively explains the tasks outlined in Table 1. Although the group is aware that some aspects of the methodology may be subject to change due to several limitations, it is anticipated that the following will occur. The exact procedures, conditions and aspects of this project will be confirmed in the near future.

4.1 Pre-Analysis: Determination of Testing Samples

In order to render credible test results, proper materials for the test samples need to be used to best quantify the realistic applications of straw bale construction. The group will performed extensive research through straw bale case studies and literature made by straw bale construction experts and homeowners to determine what materials would be best suited for the scale of the project.

Initially the group wanted to test four different types of renders under three loading conditions. According to ASTM standards, it is recommended that each test should have three specimens to maintain quality control. This would have called for storing and curing 48 test specimens. However, because of the limited space in the WPI laboratory, the group decided to scale down the project to consist of only three renders and two bales per each configuration, which would result in testing only a total of 18 bales for all three configurations.

Research showed that popular renders amongst straw bale construction include lime render, cement (plastic) stucco, and earth render. The three renders were chosen based on the availability of resources, the amount of curing time needed for each render, and the consideration of how applicable the renders would be in Massachusetts.

Although lime renders are favorable in straw bale construction in terms of breathability, the group decided not to test lime render because it takes months for lime putty to settle. Instead, it was decided that testing an earth render would be more appropriate because it is also very breathable, does not take long to cure, and materials were fairly easy and cheap to acquire.

Cement stucco is favorable in terms of durability, longevity, and low maintenance cost, which would be suiting for weather and load conditions in Massachusetts. However, as cement stucco does not allow for high rates of vapor permeability, lime is often added to cement stucco to neutralize this imbalance. As a result, a lime based cement stucco render (LMCS) was chosen.

The third test render will be of a lime based cement stucco render mixed with polyethylene fiber in order to quantify how the addition of the reinforcing fibers can affect the structural stability of straw bale wall renders.

Table 2 summarizes the final configurations of 18 specimens.

Table 2: Configurations of Testing Specimens

Load Test → Render Type ↓	Compression	Lateral	Shear
Lime Based Cement Stucco (LBCS)	A1, A2	B1, B2	C1, C2
LBCS with Polyethylene Fibers	D1, D2	E1, E2	F1, F2
Earth (Clay and Sand)	G1, G2	H1, H2	I1, I2

4.2 Preparation of Testing Procedures

4.2.1 Mixing Recipes for Renders

As there are no standards on straw bale renders as to what ingredients and quantities should be mixed, how they should be mixed and applied, or even how long it should take to cure each coat, it was essential to find mix recipes that would provide promising results for the tests that would abide by ASTM standards. Research showed that portland cement is most commonly used as a base for stucco cement renders. A mix recipe for the LBCS renders will be derived based on Quikrete's recommended ratio mix

(Quikrete Company, 2010), which abides ASTM C-926. Table 3 shows the final recipe for the render. This recipe will be used for specimens A1, A2, B1, B2, C1, and C2.

Table 3: Recipe for LBCS Render

Total Volume		Portland Cement		Hydrated Lime (Type S)		Plaster Sand	
in^3	cups	in^3	cups	in^3	cups	in^3	cups
1098.5	75.80	183.08	12.63	91.54	6.32	823.88	56.84

STRUX® 90/40 Synthetic Macro Fiber Reinforcement will be used as the polyethylene fiber because of its availability in the WPI workshop. Based on the polyethylene provider's specifications, which is to use 3.0 to 11.8 lbs. of fiber per cubic yard of concrete (W. R. Grace & Co.-Conn., 2006), 11 lbs. will be used to incorporate a best case scenario of structural integrity. With the amount of render that will be needed for the three configurations, the total amount of polyethylene needed will be .0863 lbs. These fibers will be added to the same LBCS recipe as stated in the above table and will yield the render for bales D1, D2, E1, E2, F1, and F2.

In terms of earth render, research shows that clay with a plastic consistency would be best for straw bale constructions. However, the type of clay and the exact recipe to be used will be determined based on further research.

4.2.2 Acquiring Straw Bales and Testing Quality

The bales of straw will be obtained from Harris Farm in Wethersfield, CT, one of the biggest producers of bales in the New England area. The bales are tightly bound with 2 strings, and average at 18 inches tall, 24 inches wide, and 36 inches long. The straw itself is a winter rye seed grain and was cut in June of 2010. Before rendering, bales will be measured and weighed to determine the average density of the specimens. In addition, a moisture meter will be used to record the average moisture content. These qualitative properties are critical for the tests and the analysis of the results (King, 2003).

4.1.4 Preparation of Testing Specimens

It is to be determined who will actually apply the renders on the straw bales. Because the group would like to maintain quality control on the tests, a professional renderer may be hired to complete this task. However, the group is open to other possibilities and will make decisions once all available options are identified.

4.2 Testing Procedures

This section discusses the tentative testing procedures that were determined based on the case studies of other straw bale examinations. The test results of this project will be compared to those of the case studies for bench mark analysis, which will essentially execute a more comprehensive conclusion regarding the applicability of straw bale construction in Massachusetts.

4.2.1 Compressive, Lateral and Shear Testing of Rendered Straw Bales

Once the rendered straw bales are cured, the compressive, lateral and shear load tests will be conducted on the three types of rendered bales, following the ASTM C72 standards. These three tests are highly effective in terms of determining the compressive and shear strengths of the rendered bales. Moreover, since the adhesiveness between the render and bale is also an important contributing factor to the overall strength, the shear test is designed accordingly to exemplify this factor.

Before conducting the load tests on the bales, small cubes of render sized 2 inches by 2 inches will be made and tested according to ASTM C1328-05 for quality control. In other words, these test cubes will be placed under compressive loads to evaluate the compressive strength of the renders. Such tests will help the group determine the quality of the renders used in order to quantify the conditions of the test results for the rendered bales.

Next, compressive, lateral and shear tests will be conducted on the specimens. Rendered bales will be placed on a support platform and will be loaded on top with a ½ inch steel plate and other special fixture that will be added to the head of the universal test machine in order to distribute the forces evenly. Figures 1, 2 and3 show the configurations for the three loading tests. For lateral load test (see Figure 3), the platform only supports half of the specimen and leaves the other half free to be loaded on top. By setting up the test in this way, a shear plane will be created, as shown in the figure, and the effect of the lateral load on the shear plane will be analyzed.

In terms of the shear test (see Figure 2), the platform only supports the bale and leaves the two render skins free to be loaded on top, so that the shear between the render and the bale can be tested.

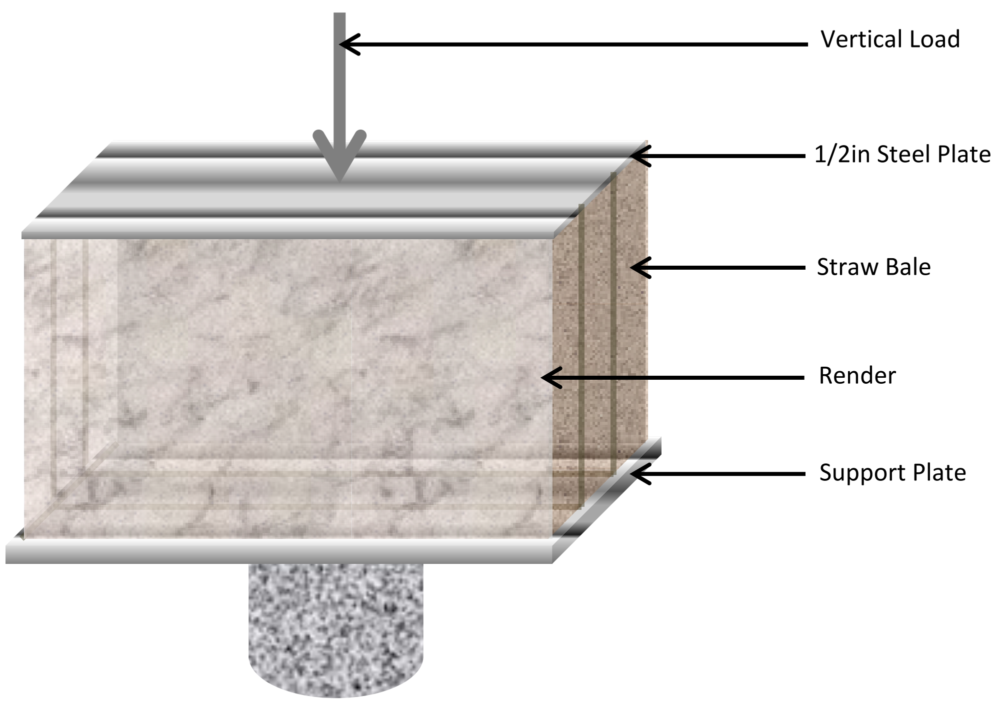

Figure 1: Compression Load Test of Rendered Straw Bale

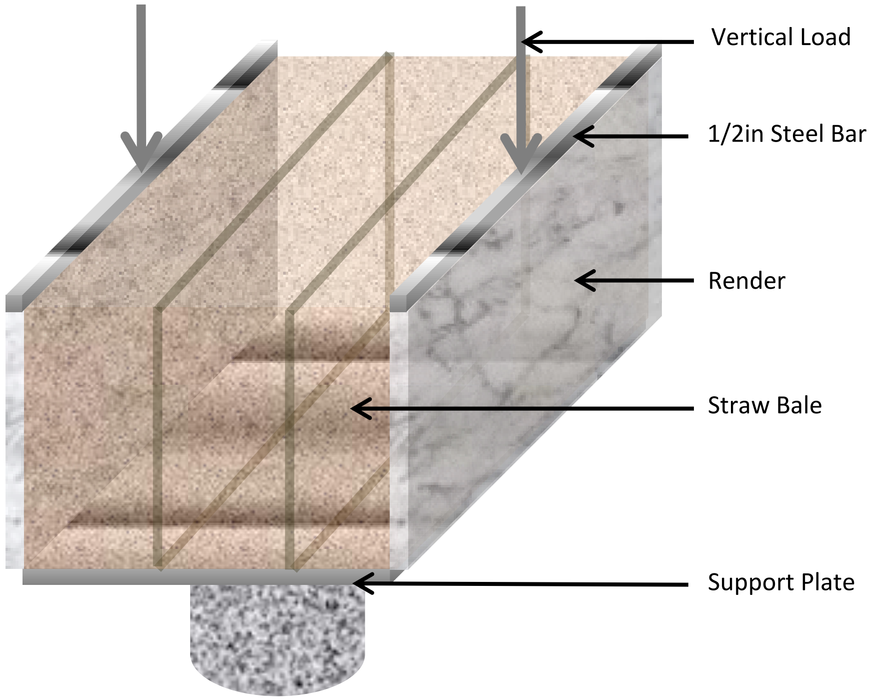

Figure 2: Shear Load Test of Rendered Straw Bale

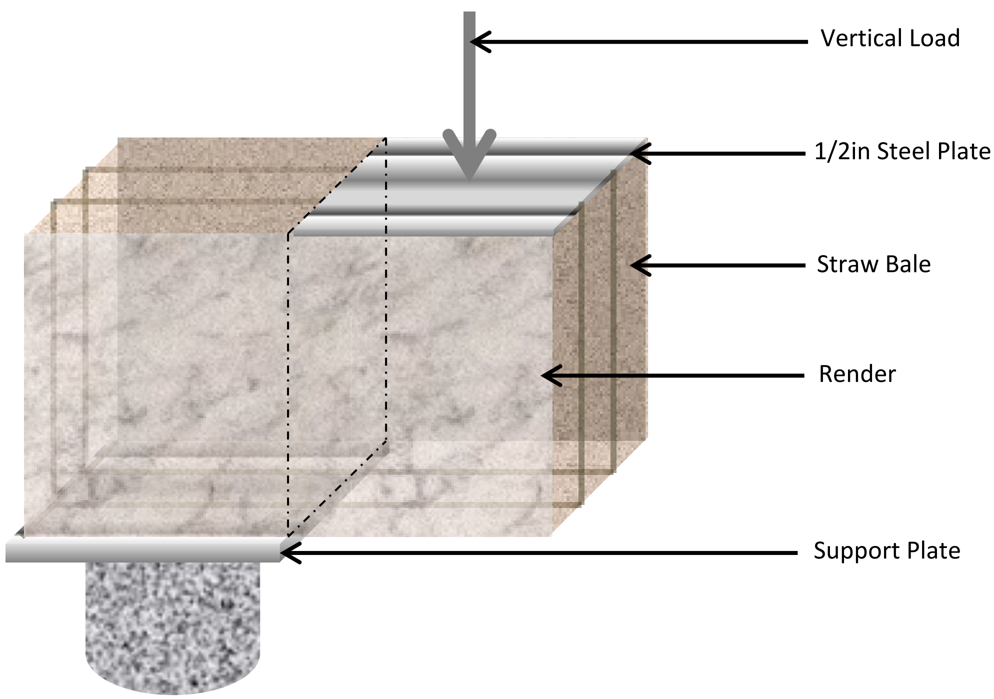

Figure 3: Lateral Load Test of Rendered Straw Bale

Vertical load will be continuously applied until the break of the first string, which is considered the failure load. Procedures will be videotaped and observations of how the bale behaves will be recorded. Load verses displacement diagrams and stress verses strain diagrams will be obtained and analyzed to determine the modulus of elasticity, and compressive and shear strengths of the rendered bales. The best render type in terms of structural strength will also be determined.

4.2.2 Determining the Thermal Resistance (R-value) of Rendered Straw Bales

A test will be performed on the rendered straw bale in order to determine the thermal resistance, also known as the R-value. The R-value will be determined by using the ASTM C 177-04 Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate. This test will be carried out by using two identical (as much as possible) specimens that are placed on a guarded-hot-plate apparatus that will measure the heat flow between the two specimens. Thermocouples will be used as the device which measures the temperature of the specimens. The heat flow, metered section area, heat flux, density and thermal resistance will be calculated as follows:

Table 4: Equations of Calculating R-values

Heat Flow	$Q = E \ x \ I$	Q=Power, E=electromotive force I= current
Metered Section Area	$A = A_m + \frac{A_g}{2}$	A=metered area section A_m= area of the guarded hot plate A_g = area of the gap
Heat Flux	$q = \frac{Q}{A}$	q= heat flux Q= heat flow A=total metered section area
Thermal Resistance	$R = \frac{\Delta T}{q}$	R=thermal resistance ΔT= change of temperature

4.2.3 Determining the Breathability of Renders

The water vapor transmission within the four different types of renders is to be determined. This test will be performed using 2 inch by 2 inch render cubes following ASTM E

96/E 96M-05 Standard Test Methods for Water Vapor Transmission of Material. Each sample will be placed and sealed on a test dish which is filled with distilled water which is ¾ ± ¼ in. from the sample. This apparatus will be monitored carefully. The water vapor transmission will be calculated as follows:

Water Vapor Transmission: $WVT = \frac{G}{tA}$

Where G= weight change

t= time during which G occurred

A= test area

WVT= rate of water vapor transmissinoton

The results of WVT will show how "breathable" or how fast the water vapor can transmit through the renders. Comparing the results with that of other building materials will provide a good insight into the breathability of the renders.

4.3 Design of a Straw Bale Structure in Worcester, MA

In order to investigate the applicability of straw bale construction in Massachusetts, the group will design a one-family two-story straw bale house following the CMR standards for one- and two-family dwellings. The house will be located in Worcester and correspond to local design loads including dead, live, wind and snow loads, which will be determined from CMR.

Once the allowable building area and building height are determined, the floor plans of the house will be laid out using AutoCAD and other design software. When designing without a specific client in mind, the layout of the house will be shaped around the needs of a modern lifestyle, as well as current trends in home design, while keeping the design flexible. A house that can accommodate a variety of lifestyles and types of households is much less likely to require remodeling later on (University of Minnesota, 2000). Taking into consideration the local climate of the building site, the group will orient the building in such way that best implements energy efficient heating.

Once the floor plans are designed, a straw bale construction method, either load bearing, or infill with wood frame, will be chosen. Techniques for construction elements such as foundation, wall, floor and roof will be evaluated within the context of CMR.

4.4 Cost Analysis of Designed Straw Bale Structure

With this design, an estimated cost of building a one family, two-story straw bale house in Worcester, MA will be determined. By making this design, a careful examination will be able to take place in such a way so that the cost of labor, construction, materials, etc., will be taken into consideration. This then will be able to be executed so an appropriate estimation of a straw bale construction project can be assessed. A book called *2009 National Construction Estimator* will be used as a guide and reference to estimate the cost of the designed straw bale home.

Once the straw bale home has been designed and tagged with a cost estimation, there will then be a comparison of the cost between a conventional one family, two-story wood home in Worcester, MA and a one family, two story straw bale home (the one that will be designed) in Worcester, MA. Once this is found, a conclusion of which type of construction technique is more cost effective will be established.

Chapter 5: Capstone Design

In order to fulfill the Capstone Design degree requirement, this Major Qualifying Project will consider several real world constraints. This project will address economic, environmental, sustainability, constructability and health/safety design considerations.

- Economic

  The economic component of the capstone design will consist of a cost analysis of a one-family, two-story straw bale house in Worcester, MA. A chart will be created to list all aspects of the construction of the house including material cost, labor cost, maintenance cost, etc. The total cost will be compared to that of a traditional wood house of similar style in Worcester, MA. One goal of this project is to determine if straw bale is an economic construction material and if building with straw bale is cost effective.

- Environmental

  The environmental section of the capstone design will address factors that impact the environment during the construction process. Since straw is very plentiful, reusable, durable, and does not call for an immense amount of energy to produce, straw bale construction benefits the environment significantly.

- Sustainability

  The sustainability aspect of the design will deal with the impacts of material choice and efficiency of resource consumption throughout the life of the straw bale house that will be designed. Long-term maintenance of straw bale construction and the durability of bale walls will be evaluated.

- Constructability

The constructability component of the design will focus on the structural strength of bale walls and the construction techniques to date to enhance the strength. State building codes will be strictly followed during the design process. Integrating bale walls in the code approved construction technique is another goal of the project.

- Health and Safety

  The health and safety aspect of this project will concentrate on the liability and safety of actually constructing a straw bale structure. This entails the type of labor and tasks that will be performed to erect one such building.

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Appendix: Calculations: Determining the Needed Amount of Render

Render		Total		
Lime-Based Cement Stucco	Total Volume (cubic in)	Portland Cement (cub.in)	Hydrated Lime (Type S)(cub.in)	Plaster Sand (cub.in)
2 Cement: 1 Lime: 9 sand	1098.5	183.0833333	91.54166667	823.875
part=	91.54166667			
parts in cups	75.7965	12.63275	6.316375	56.847375
Lime-Based Cement Stucco + Fibermesh	Total Volume (cubic in)	Cement (cub.in)	Fibermesh(lb.)	
11 lbs. Fibermesh: 1 cubic yard concrete	1098.5	1098.5	0.0863	
		75.7965		

One bale = 18 x 36 x 24 inches (.45 x .9 x .6 meters)
The metric area of the render will be .0036 m (thickness) by the length and height of the straw bale
.0036 * .45 * .9 m = .0015 m3

.0015 m3 = 91.54 in3 = one rendered side
91.54 in3 *2 sides * 3 loading conditions * 2 bale samples = 1098.48 in3 for one render